

**(19) AUSTRALIAN PATENT OFFICE**

(54) Title  
**PIPELINE ACCELERATOR FOR IMPROVED COMPUTING ARCHITECTURE AND RELATED SYSTEM AND METHOD**

(51)<sup>6</sup> International Patent Classification(s)  
G06F 009/38 G06F 015/78

(21) Application No: 2003287320 (22) Application Date: 2003.10.31

(87) WIPO No: WO04/042562

(30) Priority Data

| (31) Number | (32) Date  | (33) Country |
|-------------|------------|--------------|
| 60/422,503  | 2002.10.31 | US           |
| 10/683,929  | 2003.10.09 | US           |
| 10/683,932  | 2003.10.09 | US           |
| 10/684,053  | 2003.10.09 | US           |
| 10/684,057  | 2003.10.09 | US           |
| 10/684,102  | 2003.10.09 | US           |
|             |            | 7            |

(43) Publication Date : 2004.06.07  
(43) Publication Journal Date : 2004.07.01

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(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization International Bureau



(43) International Publication Date  
21 May 2004 (21.05.2004)

PCT

(10) International Publication Number  
**WO 2004/042562 A2**

(51) International Patent Classification<sup>7</sup>: G06F 9/38, 15/78

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(21) International Application Number:

PCT/US2003/034558

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(22) International Filing Date: 31 October 2003 (31.10.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

|            |                              |    |
|------------|------------------------------|----|
| 60/422,503 | 31 October 2002 (31.10.2002) | US |
| 10/683,929 | 9 October 2003 (09.10.2003)  | US |
| 10/683,932 | 9 October 2003 (09.10.2003)  | US |
| 10/684,053 | 9 October 2003 (09.10.2003)  | US |
| 10/684,057 | 9 October 2003 (09.10.2003)  | US |
| 10/684,102 | 9 October 2003 (09.10.2003)  | US |

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier application:

US 60/422,503 (CIP)  
Filed on 31 October 2002 (31.10.2002)

(84) Designated States (*regional*): ARIPO patent (BW, GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI patent (BJ, CE, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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Published:

— without international search report and to be republished upon receipt of that report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

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(54) Title: PIPELINE ACCELERATOR FOR IMPROVED COMPUTING ARCHITECTURE AND RELATED SYSTEM AND METHOD

(57) Abstract: A pipeline accelerator includes a memory and a hardwired-pipeline circuit coupled to the memory. The hardwired-pipeline circuit is operable to receive data, load the data into the memory, retrieve the data from the memory, process the retrieved data, and provide the processed data to an external source. In addition or in the alternative, the hardwired-pipeline circuit is operable to receive data, process the received data, load the processed data into the memory, retrieve the processed data from the memory, and provide the retrieved processed data to an external source. Where the pipeline accelerator is coupled to a processor as part of a peer-vector machine, the memory facilitates the transfer of data - whether unidirectional or bidirectional - between the hardwired-pipeline circuit(s) and an application that the processor executes.

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**PIPELINE ACCELERATOR FOR IMPROVED COMPUTING ARCHITECTURE  
AND RELATED SYSTEM AND METHOD**

**CLAIM OF PRIORITY**

[1] This application claims priority to U.S. Provisional Application Serial No. 60/422,503, filed on October 31, 2002, which is incorporated by reference.

**CROSS REFERENCE TO RELATED APPLICATIONS**

[2] This application is related to U.S. Patent App. Serial Nos. 10/684,102 entitled IMPROVED COMPUTING ARCHITECTURE AND RELATED SYSTEM AND METHOD, 10/684,053 entitled COMPUTING MACHINE HAVING IMPROVED COMPUTING ARCHITECTURE AND RELATED SYSTEM AND METHOD, 10/684,057 entitled PROGRAMMABLE CIRCUIT AND RELATED COMPUTING MACHINE AND METHOD, and 10/683,932 entitled PIPELINE ACCELERATOR HAVING MULTIPLE PIPELINE UNITS AND RELATED COMPUTING MACHINE AND METHOD, all filed on October 9, 2003, and having a common owner, and which are incorporated by reference.

**BACKGROUND**

[3] A common computing architecture for processing relatively large amounts of data in a relatively short period of time includes multiple interconnected processors that share the processing burden. By sharing the processing burden, these multiple processors can often process the data more quickly than a single processor can for a given clock frequency. For example, each of the processors can process a respective portion of the data or execute a respective portion of a processing algorithm.

[4] FIG. 1 is a schematic block diagram of a conventional computing machine **10** having a multi-processor architecture. The machine **10** includes a master processor **12** and coprocessors **14<sub>1</sub>** – **14<sub>n</sub>**, which communicate with each other and the master processor via a bus **16**, an input port **18** for receiving raw data from a remote device (not shown in FIG. 1), and an output port **20** for providing processed data to the remote source. The machine **10** also includes a memory **22** for the master processor **12**, respective memories **24<sub>1</sub>** – **24<sub>n</sub>** for the coprocessors **14<sub>1</sub>** – **14<sub>n</sub>**, and a local bus **26** for connecting the master processor **12** and the coprocessors **14<sub>1</sub>** – **14<sub>n</sub>**.

–  $14_n$ , and a memory **26** that the master processor and coprocessors share via the bus **16**. The memory **22** serves as both a program and a working memory for the master processor **12**, and each memory **24<sub>1</sub>** – **24<sub>n</sub>** serves as both a program and a working memory for a respective coprocessor **14<sub>1</sub>** – **14<sub>n</sub>**. The shared memory **26** allows the master processor **12** and the coprocessors **14** to transfer data among themselves, and from/to the remote device via the ports **18** and **20**, respectively. The master processor **12** and the coprocessors **14** also receive a common clock signal that controls the speed at which the machine **10** processes the raw data.

[5] In general, the computing machine **10** effectively divides the processing of raw data among the master processor **12** and the coprocessors **14**. The remote source (not shown in FIG. 1) such as a sonar array loads the raw data via the port **18** into a section of the shared memory **26**, which acts as a first-in-first-out (FIFO) buffer (not shown) for the raw data. The master processor **12** retrieves the raw data from the memory **26** via the bus **16**, and then the master processor and the coprocessors **14** process the raw data, transferring data among themselves as necessary via the bus **16**. The master processor **12** loads the processed data into another FIFO buffer (not shown) defined in the shared memory **26**, and the remote source retrieves the processed data from this FIFO via the port **20**.

[6] In an example of operation, the computing machine **10** processes the raw data by sequentially performing  $n + 1$  respective operations on the raw data, where these operations together compose a processing algorithm such as a Fast Fourier Transform (FFT). More specifically, the machine **10** forms a data-processing pipeline from the master processor **12** and the coprocessors **14**. For a given frequency of the clock signal, such a pipeline often allows the machine **10** to process the raw data faster than a machine having only a single processor.

[7] After retrieving the raw data from the raw-data FIFO (not shown) in the memory **26**, the master processor **12** performs a first operation, such as a trigonometric function, on the raw data. This operation yields a first result, which the processor **12** stores in a first-result FIFO (not shown) defined within the memory **26**. Typically, the processor **12** executes a program stored in the memory **22**, and performs the above-described actions under the control of the program. The

processor **12** may also use the memory **22** as working memory to temporarily store data that the processor generates at intermediate intervals of the first operation.

[8] Next, after retrieving the first result from the first-result FIFO (not shown) in the memory **26**, the coprocessor **14<sub>1</sub>** performs a second operation, such 5 as a logarithmic function, on the first result. This second operation yields a second result, which the coprocessor **14<sub>1</sub>** stores in a second-result FIFO (not shown) defined within the memory **26**. Typically, the coprocessor **14<sub>1</sub>** executes a program stored in the memory **24<sub>1</sub>**, and performs the above-described actions under the control of the program. The coprocessor **14<sub>1</sub>** may also use the memory **24<sub>1</sub>** as working memory to 10 temporarily store data that the coprocessor generates at intermediate intervals of the second operation.

[9] Then, the coprocessors **24<sub>2</sub>** – **24<sub>n</sub>** sequentially perform third –  $n^{\text{th}}$  operations on the second –  $(n-1)^{\text{th}}$  results in a manner similar to that discussed above for the coprocessor **24<sub>1</sub>**.

15 [10] The  $n^{\text{th}}$  operation, which is performed by the coprocessor **24<sub>n</sub>**, yields the final result, i.e., the processed data. The coprocessor **24<sub>n</sub>** loads the processed data into a processed-data FIFO (not shown) defined within the memory **26**, and the remote device (not shown in FIG. 1) retrieves the processed data from this FIFO.

20 [11] Because the master processor **12** and coprocessors **14** are simultaneously performing different operations of the processing algorithm, the computing machine **10** is often able to process the raw data faster than a computing machine having a single processor that sequentially performs the different operations. Specifically, the single processor cannot retrieve a new set of the raw data until it performs all  $n + 1$  operations on the previous set of raw data. But using 25 the pipeline technique discussed above, the master processor **12** can retrieve a new set of raw data after performing only the first operation. Consequently, for a given clock frequency, this pipeline technique can increase the speed at which the machine **10** processes the raw data by a factor of approximately  $n + 1$  as compared to a single-processor machine (not shown in FIG. 1).

30 [12] Alternatively, the computing machine **10** may process the raw data in parallel by simultaneously performing  $n + 1$  instances of a processing algorithm,

such as an FFT, on the raw data. That is, if the algorithm includes  $n + 1$  sequential operations as described above in the previous example, then each of the master processor **12** and the coprocessors **14** sequentially perform all  $n + 1$  operations on respective sets of the raw data. Consequently, for a given clock frequency, this  
5 parallel-processing technique, like the above-described pipeline technique, can increase the speed at which the machine **10** processes the raw data by a factor of approximately  $n + 1$  as compared to a single-processor machine (not shown in FIG. 1).

[13] Unfortunately, although the computing machine **10** can process data  
10 more quickly than a single-processor computer machine (not shown in FIG. 1), the data-processing speed of the machine **10** is often significantly less than the frequency of the processor clock. Specifically, the data-processing speed of the computing machine **10** is limited by the time that the master processor **12** and coprocessors **14** require to process data. For brevity, an example of this speed  
15 limitation is discussed in conjunction with the master processor **12**, although it is understood that this discussion also applies to the coprocessors **14**. As discussed above, the master processor **12** executes a program that controls the processor to manipulate data in a desired manner. This program includes a sequence of instructions that the processor **12** executes. Unfortunately, the processor **12**  
20 typically requires multiple clock cycles to execute a single instruction, and often must execute multiple instructions to process a single value of data. For example, suppose that the processor **12** is to multiply a first data value A (not shown) by a second data value B (not shown). During a first clock cycle, the processor **12** retrieves a multiply instruction from the memory **22**. During second and third clock  
25 cycles, the processor **12** respectively retrieves A and B from the memory **26**. During a fourth clock cycle, the processor **12** multiplies A and B, and, during a fifth clock cycle, stores the resulting product in the memory **22** or **26** or provides the resulting product to the remote device (not shown). This is a best-case scenario, because in many cases the processor **12** requires additional clock cycles for overhead tasks  
30 such as initializing and closing counters. Therefore, at best the processor **12** requires five clock cycles, or an average of 2.5 clock cycles per data value, to process A and B..

- [14] Consequently, the speed at which the computing machine **10** processes data is often significantly lower than the frequency of the clock that drives the master processor **12** and the coprocessors **14**. For example, if the processor **12** is clocked at 1.0 Gigahertz (GHz) but requires an average of 2.5 clock cycles per 5 data value, then the effective data-processing speed equals  $(1.0 \text{ GHz})/2.5 = 0.4 \text{ GHz}$ . This effective data-processing speed is often characterized in units of operations per second. Therefore, in this example, for a clock speed of 1.0 GHz, the processor **12** would be rated with a data-processing speed of 0.4 Gigaoperations/second (Gops).
- 10 [15] **FIG. 2** is a block diagram of a hardwired data pipeline **30** that can typically process data faster than a processor can for a given clock frequency, and often at substantially the same rate at which the pipeline is clocked. The pipeline **30** includes operator circuits **32<sub>1</sub>** – **32<sub>n</sub>**, which each perform a respective operation on respective data without executing program instructions. That is, the desired 15 operation is “burned in” to a circuit **32** such that it implements the operation automatically, without the need of program instructions. By eliminating the overhead associated with executing program instructions, the pipeline **30** can typically perform more operations per second than a processor can for a given clock frequency.
- 20 [16] For example, the pipeline **30** can often solve the following equation faster than a processor can for a given clock frequency:

$$Y(x_k) = (5x_k + 3)2^{x_k}$$

where  $x_k$  represents a sequence of raw data values. In this example, the operator circuit **32<sub>1</sub>** is a multiplier that calculates  $5x_k$ , the circuit **32<sub>2</sub>** is an adder that calculates  $5x_k + 3$ , and the circuit **32<sub>n</sub>** ( $n = 3$ ) is a multiplier that calculates  $(5x_k + 3)2^{x_k}$ .

- 25 [17] During a first clock cycle  $k=1$ , the circuit **32<sub>1</sub>** receives data value  $x_1$  and multiplies it by 5 to generate  $5x_1$ .
- [18] During a second clock cycle  $k = 2$ , the circuit **32<sub>2</sub>** receives  $5x_1$  from the circuit **32<sub>1</sub>** and adds 3 to generate  $5x_1 + 3$ . Also, during the second clock cycle, the circuit **32<sub>1</sub>** generates  $5x_2$ .
- 30 [19] During a third clock cycle  $k = 3$ , the circuit **32<sub>3</sub>** receives  $5x_1 + 3$  from the circuit **32<sub>2</sub>** and multiplies by  $2^{x_1}$  (effectively left shifts  $5x_1 + 3$  by  $x_1$ ) to generate

the first result  $(5x_1 + 3)2^{x^1}$ . Also during the third clock cycle, the circuit **32<sub>1</sub>** generates  $5x_3$  and the circuit **32<sub>2</sub>** generates  $5x_2 + 3$ .

[20] The pipeline **30** continues processing subsequent raw data values  $x_k$  in this manner until all the raw data values are processed.

5 [21] Consequently, a delay of two clock cycles after receiving a raw data value  $x_1$  — this delay is often called the latency of the pipeline **30** — the pipeline generates the result  $(5x_1 + 3)2^{x^1}$ , and thereafter generates one result — e.g.,  $(5x_2 + 3)2^{x^2}$ ,  $(5x_3 + 3)2^{x^3}$ , . . . ,  $(5x_n + 3)2^{x^n}$  — each clock cycle.

10 [22] Disregarding the latency, the pipeline **30** thus has a data-processing speed equal to the clock speed. In comparison, assuming that the master processor **12** and coprocessors **14** (FIG. 1) have data-processing speeds that are 0.4 times the clock speed as in the above example, the pipeline **30** can process data 2.5 times faster than the computing machine **10** (FIG. 1) for a given clock speed.

15 [23] Still referring to FIG. 2, a designer may choose to implement the pipeline **30** in a programmable logic IC (PLIC), such as a field-programmable gate array (FPGA), because a PLIC allows more design and modification flexibility than does an application specific IC (ASIC). To configure the hardwired connections within a PLIC, the designer merely sets interconnection-configuration registers disposed within the PLIC to predetermined binary states. The combination of all 20 these binary states is often called "firmware." Typically, the designer loads this firmware into a nonvolatile memory (not shown in FIG. 2) that is coupled to the PLIC. When one "turns on" the PLIC, it downloads the firmware from the memory into the interconnection-configuration registers. Therefore, to modify the functioning of the PLIC, the designer merely modifies the firmware and allows the PLIC to download 25 the modified firmware into the interconnection-configuration registers. This ability to modify the PLIC by merely modifying the firmware is particularly useful during the prototyping stage and for upgrading the pipeline **30** "in the field".

30 [24] Unfortunately, the hardwired pipeline **30** may not be the best choice to execute algorithms that entail significant decision making, particularly nested decision making. A processor can typically execute a nested-decision-making instruction (e.g., a nested conditional instruction such as "if A, then do B, else if C,

do D, . . . , else do n") approximately as fast as it can execute an operational instruction (e.g., "A + B") of comparable length. But although the pipeline 30 may be able to make a relatively simple decision (e.g., "A > B?") efficiently, it typically cannot execute a nested decision (e.g., "if A, then do B, else if C, do D, . . . , else do n") as 5 efficiently as a processor can. One reason for this inefficiency is that the pipeline 30 may have little on-board memory, and thus may need to access external working/instruction memory (not shown). And although one may be able to design the pipeline 30 to execute such a nested decision, the size and complexity of the required circuitry often makes such a design impractical, particularly where an 10 algorithm includes multiple different nested decisions.

[25] Consequently, processors are typically used in applications that require significant decision making, and hardwired pipelines are typically limited to "number crunching" applications that entail little or no decision making.

[26] Furthermore, as discussed below, it is typically much easier for one to 15 design/modify a processor-based computing machine, such as the computing machine 10 of FIG. 1, than it is to design/modify a hardwired pipeline such as the pipeline 30 of FIG. 2, particularly where the pipeline 30 includes multiple PLICs.

[27] Computing components, such as processors and their peripherals (e.g., memory), typically include industry-standard communication interfaces that 20 facilitate the interconnection of the components to form a processor-based computing machine.

[28] Typically, a standard communication interface includes two layers: a physical layer and a services layer.

[29] The physical layer includes the circuitry and the corresponding circuit 25 interconnections that form the interface and the operating parameters of this circuitry. For example, the physical layer includes the pins that connect the component to a bus, the buffers that latch data received from the pins, and the drivers that drive signals onto the pins. The operating parameters include the acceptable voltage range of the data signals that the pins receive, the signal timing 30 for writing and reading data, and the supported modes of operation (e.g., burst

mode, page mode). Conventional physical layers include transistor-transistor logic (TTL) and RAMBUS.

[30] The services layer includes the protocol by which a computing component transfers data. The protocol defines the format of the data and the manner in which the component sends and receives the formatted data.

5 Conventional communication protocols include file-transfer protocol (FTP) and transmission control protocol/internet protocol (TCP/IP).

[31] Consequently, because manufacturers and others typically design computing components having industry-standard communication interfaces, one can typically design the interface of such a component and interconnect it to other computing components with relatively little effort. This allows one to devote most of his time to designing the other portions of the computing machine, and to easily modify the machine by adding or removing components.

[32] Designing a computing component that supports an industry-standard communication interface allows one to save design time by using an existing physical-layer design from a design library. This also insures that he/she can easily interface the component to off-the-shelf computing components.

[33] And designing a computing machine using computing components that support a common industry-standard communication interface allows the designer to interconnect the components with little time and effort. Because the components support a common interface, the designer can interconnect them via a system bus with little design effort. And because the supported interface is an industry standard, one can easily modify the machine. For example, one can add different components and peripherals to the machine as the system design evolves, or can easily add/design next-generation components as the technology evolves. Furthermore, because the components support a common industry-standard service layer, one can incorporate into the computing machine's software an existing software module that implements the corresponding protocol. Therefore, one can interface the components with little effort because the interface design is essentially already in place, and thus can focus on designing the portions (e.g., software) of the machine that cause the machine to perform the desired function(s).

[34] But unfortunately, there are no known industry-standard services layers for components, such as PLICs, used to form hardwired pipelines such as the pipeline 30 of FIG. 2.

[35] Consequently, to design a pipeline having multiple PLICs, one typically 5 spends a significant amount of time and exerts a significant effort designing and debugging the services layer of the communication interface between the PLICs "from scratch." Typically, such an ad hoc services layer depends on the parameters of the data being transferred between the PLICs. Likewise, to design a pipeline that interfaces to a processor, one would have to spend a significant amount of time and 10 exert a significant effort in designing and debugging the services layer of the communication interface between the pipeline and the processor from scratch.

[36] Similarly, to modify such a pipeline by adding a PLIC to it, one typically 15 spends a significant amount of time and exerts a significant effort designing and debugging the services layer of the communication interface between the added PLIC and the existing PLICs. Likewise, to modify a pipeline by adding a processor, or to modify a computing machine by adding a pipeline, one would have to spend a significant amount of time and exert a significant effort in designing and debugging the services layer of the communication interface between the pipeline and processor.

20 [37] Consequently, referring to FIGS. 1 and 2, because of the difficulties in interfacing multiple PLICs and in interfacing a processor to a pipeline, one is often forced to make significant tradeoffs when designing a computing machine. For example, with a processor-based computing machine, one is forced to trade number-crunching speed and design/modification flexibility for complex decision- 25 making ability. Conversely, with a hardwired pipeline-based computing machine, one is forced to trade complex-decision-making ability and design/modification flexibility for number-crunching speed. Furthermore, because of the difficulties in interfacing multiple PLICs, it is often impractical for one to design a pipeline-based machine having more than a few PLICs. As a result, a practical pipeline-based 30 machine often has limited functionality. And because of the difficulties in interfacing a processor to a PLIC, it would be impractical to interface a processor to more than

one PLIC. As a result, the benefits obtained by combining a processor and a pipeline would be minimal.

[38] Therefore, a need has arisen for a new computing architecture that allows one to combine the decision-making ability of a processor-based machine 5 with the number-crunching speed of a hardwired-pipeline-based machine.

#### SUMMARY

[39] According to an embodiment of the invention, a pipeline accelerator includes a memory and a hardwired-pipeline circuit coupled to the memory. The hardwired-pipeline circuit is operable to receive data, load the data into the memory, 10 retrieve the data from the memory, process the retrieved data, and provide the processed data to an external source.

[40] According to another embodiment of the invention, the hardwired-pipeline circuit is operable to receive data, process the received data, load the processed data into the memory, retrieve the processed data from the 15 memory, and provide the retrieved processed data to an external source.

[41] Where the pipeline accelerator is coupled to a processor as part of a peer-vector machine, the memory facilitates the transfer of data — whether unidirectional or bidirectional — between the hardwired-pipeline circuit and an application that the processor executes.

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#### BRIEF DESCRIPTION OF THE DRAWINGS

[42] FIG. 1 is a block diagram of a computing machine having a conventional multi-processor architecture.

[43] FIG. 2 is a block diagram of a conventional hardwired pipeline.

[44] FIG. 3 is a block diagram of a computing machine having a peer-vector 25 architecture according to an embodiment of the invention.

[45] FIG. 4 is a block diagram of the pipeline accelerator of FIG. 3 according to an embodiment of the invention.

[46] FIG. 5 is a block diagram of the hardwired-pipeline circuit and the data memory of FIG. 4 according to an embodiment of the invention.

[47] FIG. 6 is a block diagram of the memory-write interfaces of the communication shell of FIG. 5 according to an embodiment of the invention.

[48] FIG. 7 is a block diagram of the memory-read interfaces of the communication shell of FIG. 5 according to an embodiment of the invention.

5 [49] FIG. 8 is a block diagram of the pipeline accelerator of FIG. 3 according to another embodiment of the invention.

[50] FIG. 9 is a block diagram of the hardwired-pipeline circuit and the data memory of FIG. 8 according to an embodiment of the invention.

#### DETAILED DESCRIPTION

10 [51] FIG. 3 is a schematic block diagram of a computing machine 40, which has a peer-vector architecture according to an embodiment of the invention. In addition to a host processor 42, the peer-vector machine 40 includes a pipeline accelerator 44, which performs at least a portion of the data processing, and which thus effectively replaces the bank of coprocessors 14 in the computing machine 10  
15 of FIG. 1. Therefore, the host-processor 42 and the accelerator 44 (or units thereof as discussed below) are "peers" that can transfer data vectors back and forth. Because the accelerator 44 does not execute program instructions, it typically performs mathematically intensive operations on data significantly faster than a bank of coprocessors can for a given clock frequency. Consequently, by combining the  
20 decision-making ability of the processor 42 and the number-crunching ability of the accelerator 44, the machine 40 has the same abilities as, but can often process data faster than, a conventional computing machine such as the machine 10.  
Furthermore, as discussed below, providing the accelerator 44 with a  
25 communication interface that is compatible with the communication interface of the host processor 42 facilitates the design and modification of the machine 40, particularly where the processor's communication interface is an industry standard. And where the accelerator 44 includes multiple pipeline units (e.g., PLIC-based circuits), providing each of these units with the same communication interface facilitates the design and modification of the accelerator, particularly where the  
30 communication interfaces are compatible with an industry-standard interface.

Moreover, the machine **40** may also provide other advantages as described below and in the previously cited patent applications.

[52] Still referring to FIG. 3, in addition to the host processor **42** and the pipeline accelerator **44**, the peer-vector computing machine **40** includes a processor memory **46**, an interface memory **48**, a bus **50**, a firmware memory **52**, an optional raw-data input port **54**, a processed-data output port **58**, and an optional router **61**.

[53] The host processor **42** includes a processing unit **62** and a message handler **64**, and the processor memory **46** includes a processing-unit memory **66** and a handler memory **68**, which respectively serve as both program and working memories for the processor unit and the message handler. The processor memory **46** also includes an accelerator-configuration registry **70** and a message-configuration registry **72**, which store respective configuration data that allow the host processor **42** to configure the functioning of the accelerator **44** and the format of the messages that the message handler **64** sends and receives.

[54] The pipeline accelerator **44** is disposed on at least one PLIC (not shown) and includes hardwired pipelines **74<sub>1</sub>** – **74<sub>n</sub>**, which process respective data without executing program instructions. The firmware memory **52** stores the configuration firmware for the accelerator **44**. If the accelerator **44** is disposed on multiple PLICs, these PLICs and their respective firmware memories may be disposed in multiple pipeline units (FIG. 4). The accelerator **44** and pipeline units are discussed further below and in previously cited U.S. Patent App. Serial No. 10/683,932 entitled PIPELINE ACCELERATOR HAVING MULTIPLE PIPELINE UNITS AND RELATED COMPUTING MACHINE AND METHOD. Alternatively, the accelerator **44** may be disposed on at least one ASIC, and thus may have internal interconnections that are unconfigurable. In this alternative, the machine **40** may omit the firmware memory **52**. Furthermore, although the accelerator **44** is shown including multiple pipelines **74**, it may include only a single pipeline. In addition, although not shown, the accelerator **44** may include one or more processors such as a digital-signal processor (DSP). Moreover, although not shown, the accelerator **44** may include a data input port and/or a data output port.

[55] The general operation of the peer-vector machine **40** is discussed in previously cited U.S. Patent App. Serial No. 10/684,102 entitled IMPROVED

COMPUTING ARCHITECTURE AND RELATED SYSTEM AND METHOD, and the structure and operation of the pipeline accelerator **44** is discussed below in conjunction with **FIGS. 4 – 9**.

[56] FIG. 4 is a schematic block diagram of the pipeline accelerator **44** of **FIG. 3** according to an embodiment of the invention.

[57] The accelerator **44** includes one or more pipeline units **78**, each of which includes a pipeline circuit **80**, such as a PLIC or an ASIC. As discussed further below and in previously cited U.S. Patent App. Serial No. 10/683,932 entitled PIPELINE ACCELERATOR HAVING MULTIPLE PIPELINE UNITS AND RELATED COMPUTING MACHINE AND METHOD, each pipeline unit **78** is a "peer" of the host processor **42** and of the other pipeline units of the accelerator **44**. That is, each pipeline unit **78** can communicate directly with the host processor **42** or with any other pipeline unit. Thus, this peer-vector architecture prevents data "bottlenecks" that otherwise might occur if all of the pipeline units **78** communicated through a central location such as a master pipeline unit (not shown) or the host processor **42**. Furthermore, it allows one to add or remove peers from the peer-vector machine **40** (**FIG. 3**) without significant modifications to the machine.

[58] The pipeline circuit **80** includes a communication interface **82**, which transfers data between a peer, such as the host processor **42** (**FIG. 3**), and the following other components of the pipeline circuit: the hardwired pipelines **74<sub>1</sub>–74<sub>n</sub>** (**FIG. 3**) via a communication shell **84**, a controller **86**, an exception manager **88**, and a configuration manager **90**. The pipeline circuit **80** may also include an industry-standard bus interface **91**. Alternatively, the functionality of the interface **91** may be included within the communication interface **82**.

[59] By designing the components of the pipeline circuit **80** as separate modules, one can often simplify the design of the pipeline circuit. That is, one can design and test each of these components separately, and then integrate them much like one does when designing software or a processor-based computing system (such as the system **10** of **FIG. 1**). In addition, one can save in a library (not shown) hardware description language (HDL) that defines these components — particularly components, such as the communication interface **82**, that will probably be used frequently in other pipeline designs — thus reducing the design and test

time of future pipeline designs that use the same components. That is, by using the HDL from the library, the designer need not redesign previously implemented components "from scratch", and thus can focus his efforts on the design of components that were not previously implemented, or on the modification of 5 previously implemented components. Moreover, one can save in the library HDL that defines multiple versions of the pipeline circuit **80** or of the entire pipeline accelerator **44**, so that one can pick and choose among existing designs.

[60] The communication interface **82** sends and receives data in a format recognized by the message handler **64** (FIG. 3), and thus typically facilitates the 10 design and modification of the peer-vector machine **40** (FIG. 3). For example, if the data format is an industry standard such as the Rapid I/O format, then one need not design a custom interface between the host processor **42** and the accelerator **44**. Furthermore, by allowing the pipeline circuit **80** to communicate with other peers, such as the host processor **42** (FIG. 3), via the pipeline bus **50** instead of via a 15 non-bus interface, one can change the number of pipeline units **78** by merely connecting or disconnecting them (or the circuit cards that hold them) to the pipeline bus instead of redesigning a non-bus interface from scratch each time a pipeline unit is added or removed.

[61] The hardwired pipelines **74<sub>1</sub>-74<sub>n</sub>** perform respective operations on data 20 as discussed above in conjunction with FIG. 3 and in previously cited U.S. Patent App. Serial No. 10/684,102 entitled IMPROVED COMPUTING ARCHITECTURE AND RELATED SYSTEM AND METHOD, and the communication shell **84** interfaces the pipelines to the other components of the pipeline circuit **80** and to circuits (such as a data memory **92** discussed below) external to the pipeline circuit.

25 [62] The controller **86** synchronizes the hardwired pipelines **74<sub>1</sub>-74<sub>n</sub>** and monitors and controls the sequence in which they perform the respective data operations in response to communications, *i.e.*, "events," from other peers. For example, a peer such as the host processor **42** may send an event to the pipeline unit **78** via the pipeline bus **50** to indicate that the peer has finished sending a block 30 of data to the pipeline unit and to cause the hardwired pipelines **74<sub>1</sub>-74<sub>n</sub>** to begin processing this data. An event that includes data is typically called a message, and an event that does not include data is typically called a "door bell." Furthermore, as

discussed below in conjunction with FIG. 5, the pipeline unit 78 may also synchronize the pipelines 74<sub>1</sub>-74<sub>n</sub> in response to a synchronization signal.

[63] The exception manager 88 monitors the status of the hardwired pipelines 74<sub>1</sub>-74<sub>n</sub>, the communication interface 82, the communication shell 84, the controller 86, and the bus interface 91, and reports exceptions to the host processor 42 (FIG. 3). For example, if a buffer in the communication interface 82 overflows, then the exception manager 88 reports this to the host processor 42. The exception manager may also correct, or attempt to correct, the problem giving rise to the exception. For example, for an overflowing buffer, the exception manager 88 may increase the size of the buffer, either directly or via the configuration manager 90 as discussed below.

[64] The configuration manager 90 sets the soft configuration of the hardwired pipelines 74<sub>1</sub>-74<sub>n</sub>, the communication interface 82, the communication shell 84, the controller 86, the exception manager 88, and the interface 91 in response to soft-configuration data from the host processor 42 (FIG. 3) — as discussed in previously cited U.S. Patent App. Serial No. 10/684,102 entitled IMPROVED COMPUTING ARCHITECTURE AND RELATED SYSTEM AND METHOD, the hard configuration denotes the actual topology, on the transistor and circuit-block level, of the pipeline circuit 80, and the soft configuration denotes the physical parameters (e.g., data width, table size) of the hard-configured components. That is, soft configuration data is similar to the data that can be loaded into a register of a processor (not shown in FIG. 4) to set the operating mode (e.g., burst-memory mode) of the processor. For example, the host processor 42 may send soft-configuration data that causes the configuration manager 90 to set the number and respective priority levels of queues in the communication interface 82. The exception manager 88 may also send soft-configuration data that causes the configuration manager 90 to, e.g., increase the size of an overflowing buffer in the communication interface 82.

[65] Still referring to FIG. 4, in addition to the pipeline circuit 80, the pipeline unit 78 of the accelerator 44 includes the data memory 92, an optional communication bus 94, and, if the pipeline circuit is a PLIC, the firmware memory 52 (FIG. 3).

[66] The data memory 92 buffers data as it flows between another peer, such as the host processor 42 (FIG. 3), and the hardwired pipelines 74<sub>1</sub>-74<sub>n</sub>, and is also a working memory for the hardwired pipelines. The communication interface 82 interfaces the data memory 92 to the pipeline bus 50 (via the communication bus 94 and industry-standard interface 91 if present), and the communication shell 84 interfaces the data memory to the hardwired pipelines 74<sub>1</sub>-74<sub>n</sub>.

[67] The industry-standard interface 91 is a conventional bus-interface circuit that reduces the size and complexity of the communication interface 82 by effectively offloading some of the interface circuitry from the communication interface. Therefore, if one wishes to change the parameters of the pipeline bus 50 or router 61 (FIG. 3), then he need only modify the interface 91 and not the communication interface 82. Alternatively, one may dispose the interface 91 in an IC (not shown) that is external to the pipeline circuit 80. Offloading the interface 91 from the pipeline circuit 80 frees up resources on the pipeline circuit for use in, e.g., the hardwired pipelines 74<sub>1</sub>-74<sub>n</sub>, and the controller 86. Or, as discussed above, the bus interface 91 may be part of the communication interface 82.

[68] As discussed above in conjunction with FIG. 3, where the pipeline circuit 80 is a PLIC, the firmware memory 52 stores the firmware that sets the hard configuration of the pipeline circuit. The memory 52 loads the firmware into the pipeline circuit 80 during the configuration of the accelerator 44, and may receive modified firmware from the host processor 42 (FIG. 3) via the communication interface 82 during or after the configuration of the accelerator. The loading and receiving of firmware is further discussed in previously cited U.S. Patent App. Serial No. 10/684,057 entitled PROGRAMMABLE CIRCUIT AND RELATED COMPUTING MACHINE AND METHOD.

[69] Still referring to FIG. 4, the pipeline circuit 80, data memory 92, and firmware memory 52 may be disposed on a circuit board or card 98, which may be plugged into a pipeline-bus connector (not shown) much like a daughter card can be plugged into a slot of a mother board in a personal computer (not shown). Although not shown, conventional ICs and components such as a power regulator and a power sequencer may also be disposed on the card 98 as is known.

[70] Further details of the structure and operation of the pipeline unit 78 are discussed below in conjunction with FIG. 5.

[71] FIG. 5 is a block diagram of the pipeline unit 78 of FIG. 4 according to an embodiment of the invention. For clarity, the firmware memory 52 is omitted from FIG. 5. The pipeline circuit 80 receives a master CLOCK signal, which drives the below-described components of the pipeline circuit either directly or indirectly. The pipeline circuit 80 may generate one or more slave clock signals (not shown) from the master CLOCK signal in a conventional manner. The pipeline circuit 80 may also receive a synchronization signal SYNC as discussed below.

10 [72] The data memory 92 includes an input dual-port-static-random-access memory (DPSRAM) 100, an output DPSRAM 102, and an optional working DPSRAM 104.

15 [73] The input DPSRAM 100 includes an input port 106 for receiving data from a peer, such as the host processor 42 (FIG. 3), via the communication interface 82, and includes an output port 108 for providing this data to the hardwired pipelines 74<sub>1</sub>-74<sub>n</sub> via the communication shell 84. Having two ports, one for data input and one for data output, increases the speed and efficiency of data transfer to/from the DPSRAM 100 because the communication interface 82 can write data to the DPSRAM while the pipelines 74<sub>1</sub>-74<sub>n</sub> read data from the DPSRAM. Furthermore, as 20 discussed above, using the DPSRAM 100 to buffer data from a peer such as the host processor 42 allows the peer and the pipelines 74<sub>1</sub>-74<sub>n</sub> to operate asynchronously relative to one and other. That is, the peer can send data to the pipelines 74<sub>1</sub>-74<sub>n</sub> without "waiting" for the pipelines to complete a current operation. Likewise, the pipelines 74<sub>1</sub>-74<sub>n</sub> can retrieve data without "waiting" for the peer to 25 complete a data-sending operation.

30 [74] Similarly, the output DPSRAM 102 includes an input port 110 for receiving data from the hardwired pipelines 74<sub>1</sub>-74<sub>n</sub> via the communication shell 84, and includes an output port 112 for providing this data to a peer, such as the host processor 42 (FIG. 3), via the communication interface 82. As discussed above, the two data ports 110 (input) and 112 (output) increase the speed and efficiency of data transfer to/from the DPSRAM 102, and using the DPSRAM 102 to buffer data from the pipelines 74<sub>1</sub>-74<sub>n</sub> allows the peer and the pipelines to operate asynchronously

relative to one another. That is, the pipelines  $74_1$ - $74_n$  can publish data to the peer without "waiting" for the output-data handler  $126$  to complete a data transfer to the peer or to another peer. Likewise, the output-data handler  $126$  can transfer data to a peer without "waiting" for the pipelines  $74_1$ - $74_n$  to complete a data-publishing

5 operation.

[75] The working DPSRAM  $104$  includes an input port  $114$  for receiving data from the hardwired pipelines  $74_1$ - $74_n$  via the communication shell  $84$ , and includes an output port  $116$  for returning this data back to the pipelines via the communication shell. While processing input data received from the DPSRAM  $100$ ,

10 the pipelines  $74_1$ - $74_n$  may need to temporarily store partially processed, *i.e.*, intermediate, data before continuing the processing of this data. For example, a first pipeline, such as the pipeline  $74_1$ , may generate intermediate data for further processing by a second pipeline, such as the pipeline  $74_2$ ; thus, the first pipeline may need to temporarily store the intermediate data until the second pipeline

15 retrieves it. The working DPSRAM  $104$  provides this temporary storage. As discussed above, the two data ports  $114$  (input) and  $116$  (output) increase the speed and efficiency of data transfer between the pipelines  $74_1$ - $74_n$  and the DPSRAM  $104$ . Furthermore, including a separate working DPSRAM  $104$  typically increases the speed and efficiency of the pipeline circuit  $80$  by allowing the DPSRAMs  $100$  and

20  $102$  to function exclusively as data-input and data-output buffers, respectively. But, with slight modification to the pipeline circuit  $80$ , either or both of the DPSRAMS  $100$  and  $102$  can also be a working memory for the pipelines  $74_1$ - $74_n$  when the DPSRAM  $104$  is omitted, and even when it is present.

[76] Although the DPSRAMS  $100$ ,  $102$ , and  $104$  are described as being external to the pipeline circuit  $80$ , one or more of these DPSRAMS, or equivalents thereto, may be internal to the pipeline circuit.

[77] Still referring to FIG. 5, the communication interface  $82$  includes an industry-standard bus adapter  $118$ , an input-data handler  $120$ , input-data and input-event queues  $122$  and  $124$ , an output-data handler  $126$ , and output-data and output-event queues  $128$  and  $130$ . Although the queues  $122$ ,  $124$ ,  $128$ , and  $130$  are shown as single queues, one or more of these queues may include sub queues (not

shown) that allow segregation by, e.g., priority, of the values stored in the queues or of the respective data that these values represent.

- [78] The industry-standard bus adapter **118** includes the physical layer that allows the transfer of data between the pipeline circuit **80** and the pipeline bus **50** (FIG. 4) via the communication bus **94**. Therefore, if one wishes to change the parameters of the bus **94**, then he need only modify the adapter **118** and not the entire communication interface **82**. Where the industry-standard bus interface **91** is omitted from the pipeline unit **78**, , then the adapter **118** may be modified to allow the transfer of data directly between the pipeline bus **50** and the pipeline circuit **80**.
- 5 In this latter implementation, the modified adapter **118** includes the functionality of the bus interface **91**, and one need only modify the adapter **118** if he/she wishes to change the parameters of the bus **50**.
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- [79] The input-data handler **120** receives data from the industry-standard adapter **118**, loads the data into the DPSRAM **100** via the input port **106**, and generates and stores a pointer to the data and a corresponding data identifier in the input-data queue **122**. If the data is the payload of a message from a peer, such as the host processor **42** (FIG. 3), then the input-data handler **120** extracts the data from the message before loading the data into the DPSRAM **100**. The input-data handler **120** includes an interface **132**, which writes the data to the input port **106** of the DPSRAM **100** and which is further discussed below in conjunction with FIG. 6. Alternatively, the input-data handler **120** can omit the extraction step and load the entire message into the DPSRAM **100**.
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- [80] The input-data handler **120** also receives events from the industry-standard bus adapter **118**, and loads the events into the input-event queue **124**.
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- [81] Furthermore, the input-data handler **120** includes a validation manager **134**, which determines whether received data or events are intended for the pipeline circuit **80**. The validation manager **134** may make this determination by analyzing the header (or a portion thereof) of the message that contains the data or the event, by analyzing the type of data or event, or the analyzing the instance identification (i.e., the hardwired pipeline **74** for which the data/event is intended) of
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the data or event. If the input-data handler **120** receives data or an event that is not intended for the pipeline circuit **80**, then the validation manager **134** prohibits the input-data handler from loading the received data/event. Where the peer-vector machine **40** includes the router **61** (FIG. 3) such that the pipeline unit **78** should 5 receive only data/events that are intended for the pipeline unit, the validation manager **134** may also cause the input-data handler **120** to send to the host processor **42** (FIG. 3) an exception message that identifies the exception (erroneously received data/event) and the peer that caused the exception.

[82] The output-data handler **126** retrieves processed data from locations of 10 the DPSRAM **102** pointed to by the output-data queue **128**, and sends the processed data to one or more peers, such as the host processor **42** (FIG. 3), via the industry-standard bus adapter **118**. The output-data handler **126** includes an interface **136**, which reads the processed data from the DPSRAM **102** via the port **112**. The interface **136** is further discussed below in conjunction with FIG. 7.

15 [83] The output-data handler **126** also retrieves from the output-event queue **130** events generated by the pipelines **74<sub>1</sub>** – **74<sub>n</sub>**, and sends the retrieved events to one or more peers, such as the host processor **42** (FIG. 3) via the industry-standard bus adapter **118**.

[84] Furthermore, the output-data handler **126** includes a subscription 20 manager **138**, which includes a list of peers, such as the host processor **42** (FIG. 3), that subscribe to the processed data and to the events; the output-data handler uses this list to send the data/events to the correct peers. If a peer prefers the data/event to be the payload of a message, then the output-data handler **126** retrieves the network or bus-port address of the peer from the subscription manager **138**, 25 generates a header that includes the address, and generates the message from the data/event and the header.

[85] Although the technique for storing and retrieving data stored in the DPSRAMS **100** and **102** involves the use of pointers and data identifiers, one may modify the input- and output-data handlers **120** and **126** to implement other 30 data-management techniques. Conventional examples of such data-management techniques include pointers using keys or tokens, input/output control (IOC) block, and spooling.

- [86] The communication shell 84 includes a physical layer that interfaces the hardwired pipelines 74<sub>1</sub>-74<sub>n</sub> to the output-data queue 128, the controller 86, and the DPSRAMs 100, 102, and 104. The shell 84 includes interfaces 140 and 142, and optional interfaces 144 and 146. The interfaces 140 and 146 may be similar to the interface 136; the interface 140 reads input data from the DPSRAM 100 via the port 108, and the interface 146 reads intermediate data from the DPSRAM 104 via the port 116. The interfaces 142 and 144 may be similar to the interface 132; the interface 142 writes processed data to the DPSRAM 102 via the port 110, and the interface 144 writes intermediate data to the DPSRAM 104 via the port 114.
- 5 [87] The controller 86 includes a sequence manager 148 and a synchronization interface 150, which receives one or more synchronization signals SYNC. A peer, such as the host processor 42 (FIG. 3), or a device (not shown) external to the peer-vector machine 40 (FIG. 3) may generate the SYNC signal, which triggers the sequence manager 148 to activate the hardwired pipelines 74<sub>1</sub>-74<sub>n</sub>, as discussed below and in previously cited U.S. Patent App. Serial No. 10/683,932 entitled PIPELINE ACCELERATOR HAVING MULTIPLE PIPELINE UNITS AND RELATED COMPUTING MACHINE AND METHOD. The synchronization interface 150 may also generate a SYNC signal to trigger the pipeline circuit 80 or to trigger another peer. In addition, the events from the input-event queue 124 also trigger the sequence manager 148 to activate the hardwired pipelines 74<sub>1</sub>-74<sub>n</sub> as discussed below.
- 10 [88] The sequence manager 148 sequences the hardwired pipelines 74<sub>1</sub>-74<sub>n</sub> through their respective operations via the communication shell 84. Typically, each pipeline 74 has at least three operating states: preprocessing, processing, and post processing. During preprocessing, the pipeline 74, e.g., initializes its registers and retrieves input data from the DPSRAM 100. During processing, the pipeline 74, e.g., operates on the retrieved data, temporarily stores intermediate data in the DPSRAM 104, retrieves the intermediate data from the DPSRAM 104, and operates on the intermediate data to generate result data. During post processing, the pipeline 74, e.g., loads the result data into the DPSRAM 102. Therefore, the sequence manager 148 monitors the operation of the pipelines 74<sub>1</sub>-74<sub>n</sub>, and instructs each pipeline when to begin each of its operating states. And one may distribute the
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pipeline tasks among the operating states differently than described above. For example, the pipeline **74** may retrieve input data from the DPSRAM **100** during the processing state instead of during the preprocessing state.

[89] Furthermore, the sequence manager **148** maintains a predetermined internal operating synchronization among the hardwired pipelines **74<sub>1</sub>-74<sub>n</sub>**. For example, to avoid all of the pipelines **74<sub>1</sub>-74<sub>n</sub>**, simultaneously retrieving data from the DPSRAM **100**, it may be desired to synchronize the pipelines such that while the first pipeline **74<sub>1</sub>** is in a preprocessing state, the second pipeline **74<sub>2</sub>** is in a processing state and the third pipeline **74<sub>3</sub>** is in a post-processing state. Because a state of one pipeline **74** may require a different number of clock cycles than a concurrently performed state of another pipeline, the pipelines **74<sub>1</sub>-74<sub>n</sub>** may lose synchronization if allowed to run freely. Consequently, at certain times there may be a "bottle neck," as, for example, multiple pipelines **74** simultaneously attempt to retrieve data from the DPSRAM **100**. To prevent the loss of synchronization and its undesirable consequences, the sequence manager **148** allows all of the pipelines **74** to complete a current operating state before allowing any of the pipelines to proceed to a next operating state. Therefore, the time that the sequence manager **148** allots for a current operating state is long enough to allow the slowest pipeline **74** to complete that state. Alternatively, circuitry (not shown) for maintaining a predetermined operating synchronization among the hardwired pipelines **74<sub>1</sub>-74<sub>n</sub>** may be included within the pipelines themselves.

[90] In addition to sequencing and internally synchronizing the hardwired pipelines **74<sub>1</sub> - 74<sub>n</sub>**, the sequence manager **148** synchronizes the operation of the pipelines to the operation of other peers, such as the host processor **42** (FIG. 3), and to the operation of other external devices in response to one or more SYNC signals or to an event in the input-events queue **124**.

[91] Typically, a SYNC signal triggers a time-critical function but requires significant hardware resources; comparatively, an event typically triggers a non-time-critical function but requires significantly fewer hardware resources. As discussed in previously cited U.S. Patent App. Serial No. 10/683,932 entitled PIPELINE ACCELERATOR HAVING MULTIPLE PIPELINE UNITS AND RELATED COMPUTING MACHINE AND METHOD, because a SYNC signal is routed directly

from peer to peer, it can trigger a function more quickly than an event, which must make its way through, e.g., the pipeline bus **50** (FIG. 3), the input-data handler **120**, and the input-event queue **124**. But because they are separately routed, the SYNC signals require dedicated circuitry, such as routing lines, buffers, and the SYNC interface **150**, of the pipeline circuit **80**. Conversely, because they use the existing data-transfer infrastructure (e.g. the pipeline bus **50** and the input-data handler **120**), the events require only the dedicated input-event queue **124**. Consequently, designers tend to use events to trigger all but the most time-critical functions.

[92] The following is an example of function triggering. Assume that a sonar sensor element (not shown) sends blocks of data to the pipeline unit **78**, the input-data handler **120** stores this data in the DPSRAM **100**, the pipeline **74<sub>1</sub>** transfers this data from the DPSRAM **100** to the DPSRAM **104**, and, when triggered, the pipeline **74<sub>2</sub>** retrieves and processes the data from the DPSRAM **104**. If the processing that the pipeline **74<sub>2</sub>** performs on the data is time critical, then the sensor element may generate a SYNC pulse to trigger the pipeline **74<sub>2</sub>**, via the interface **150** and the sequence manager **148**, as soon as the pipeline **74<sub>1</sub>** finishes loading an entire block of data into the DPSRAM **104**. There are many conventional techniques that the pipeline unit **78** and the sensor can employ to determine when the pipeline **74<sub>1</sub>** is finished. For example, as discussed below, the sequence manager **148** may provide a corresponding SYNC pulse or event to the sensor. Alternatively, if the processing that the pipeline **74<sub>2</sub>** performs is not time critical, then the sensor may send an event to the sequence manager **148** via the pipeline bus **50** (FIG. 3).

[93] The sequence manager **148** may also provide to a peer, such as the host processor **42** (FIG. 3), information regarding the operation of the hardwired pipelines **74<sub>1</sub>-74<sub>n</sub>** by generating a SYNC pulse or an event. The sequence manager **148** sends a SYNC pulse via the SYNC interface **150** and a dedicated line (not shown), and sends an event via the output-event queue **130** and the output-data handler **126**. Referring to the above example, suppose that a peer further processes the data blocks from the pipeline **74<sub>2</sub>**. The sequence manager **148** may notify the peer via a SYNC pulse or an event when the pipeline **74<sub>2</sub>** has finished processing a block of data. The sequence manager **148** may also confirm receipt of a SYNC

pulse or an event by generating and sending a corresponding SYNC pulse or event to the appropriate peer(s).

[94] Still referring to FIG. 5, the operation of the pipeline unit 78 is discussed according to an embodiment of the invention.

5 [95] For data, the industry-standard bus interface 91 receives data signals (which originates from a peer, such as the host processor 42 of FIG. 3) from the pipeline bus 50 (and the router 61 if present), and translates these signals into messages each having a header and payload.

10 [96] Next, the industry-standard bus adapter 118 converts the messages from the industry-standard bus interface 91 into a format that is compatible with the input-data handler 120.

15 [97] Then, the input-data handler 120 dissects the message headers and extracts from each header the portion that describes the data payload. For example, the extracted header portion may include, e.g., the address of the pipeline unit 78, the type of data in the payload, or an instance identifier that identifies the pipeline(s) 78<sub>1</sub> – 78<sub>n</sub> for which the data is intended.

20 [98] Next, the validation manager 134 analyzes the extracted header portion and confirms that the data is intended for one of the hardwired pipelines 74<sub>1</sub>–74<sub>n</sub>, the interface 132 writes the data to a location of the DPSRAM 100 via the port 106, and the input-data handler 120 stores a pointer to the location and a corresponding data identifier in the input-data queue 122. The data identifier identifies the pipeline or pipelines 74<sub>1</sub>–74<sub>n</sub> for which the data is intended, or includes information that allows the sequence manager 148 to make this identification as discussed below. Alternatively, the queue 122 may include a respective subqueue 25 (not shown) for each pipeline 74<sub>1</sub>–74<sub>n</sub>, and the input-data handler 120 stores the pointer in the subqueue or subqueues of the intended pipeline or pipelines. In this alternative, the data identifier may be omitted. Furthermore, if the data is the payload of a message, then the input-data handler 120 extracts the data from the message before the interface 132 stores the data in the DPSRAM 100.

30 Alternatively, as discussed above, the interface 132 may store the entire message in the DPSRAM 100.

[99] Then, at the appropriate time, the sequence manager **148** reads the pointer and the data identifier from the input-data queue **122**, determines from the data identifier the pipeline or pipelines **74<sub>1</sub> – 74<sub>n</sub>** for which the data is intended, and passes the pointer to the pipeline or pipelines via the communication shell **84**.

5 [100] Next, the data-receiving pipeline or pipelines **74<sub>1</sub> – 74<sub>n</sub>** cause the interface **140** to retrieve the data from the pointed-to location of the DPSRAM **100** via the port **108**.

[101] Then, the data-receiving pipeline or pipelines **74<sub>1</sub>-74<sub>n</sub>** process the retrieved data, the interface **142** writes the processed data to a location of the  
10 DPSRAM **102** via the port **110**, and the communication shell **84** loads into the output-data queue **128** a pointer to and a data identifier for the processed data. The data identifier identifies the destination peer or peers, such as the host processor **42** (FIG. 3), that subscribe to the processed data, or includes information (such as the data type) that allows the subscription manager **138** to subsequently determine the  
15 destination peer or peers (e.g., the host processor **42** of FIG. 3). Alternatively, the queue **128** may include a respective subqueue (not shown) for each pipeline **74<sub>1</sub>-74<sub>n</sub>**, and the communication shell **84** stores the pointer in the subqueue or subqueues of the originating pipeline or pipelines. In this alternative, the communication shell **84** may omit loading a data identifier into the queue **128**.  
20 Furthermore, if the pipeline or pipelines **74<sub>1</sub>-74<sub>n</sub>** generate intermediate data while processing the retrieved data, then the interface **144** writes the intermediate data into the DPSRAM **104** via the port **114**, and the interface **146** retrieves the intermediate data from the DPSRAM **104** via the port **116**.

[102] Next, the output-data handler **126** retrieves the pointer and the data identifier from the output-data queue **128**, the subscription manager **138** determines from the identifier the destination peer or peers (e.g., the host processor **42** of FIG. 3) of the data, the interface **136** retrieves the data from the pointed-to location of the DPSRAM **102** via the port **112**, and the output-data handler sends the data to the industry-standard bus adapter **118**. If a destination peer requires the data to be the payload of a message, then the output-data handler **126** generates the message and sends the message to the adapter **118**. For example, suppose the data has multiple destination peers and the pipeline bus **50** supports message broadcasting.  
30

The output-data handler **126** generates a single header that includes the addresses of all the destination peers, combines the header and data into a message, and sends (via the adapter **118** and the industry-standard bus interface **91**) a single message to all of the destination peers simultaneously. Alternatively, the output-data handler **126** generates a respective header, and thus a respective message, for each destination peer, and sends each of the messages separately.

5 [103] Then, the industry-standard bus adapter **118** formats the data from the output-data handler **126** so that it is compatible with the industry-standard bus interface **91**.

10 [104] Next, the industry-standard bus interface **91** formats the data from the industry-standard bus adapter **118** so that it is compatible with the pipeline bus **50** (FIG. 3).

15 [105] For an event with no accompanying data, i.e., a doorbell, the industry-standard bus interface **91** receives a signal (which originates from a peer, such as the host processor **42** of FIG. 3) from the pipeline bus **50** (and the router **61** if present), and translates the signal into a header (i.e., a data-less message) that includes the event.

20 [106] Next, the industry-standard bus adapter **118** converts the header from the industry-standard bus interface **91** into a format that is compatible with the input-data handler **120**.

[107] Then, the input-data handler **120** extracts from the header the event and a description of the event. For example, the description may include, e.g., the address of the pipeline unit **78**, the type of event, or an instance identifier that identifies the pipeline(s) **78<sub>1</sub> – 78<sub>n</sub>** for which the event is intended.

25 [108] Next, the validation manager **134** analyzes the event description and confirms that the event is intended for one of the hardwired pipelines **74<sub>1</sub>–74<sub>n</sub>**, and the input-data handler **120** stores the event and its description in the input-event queue **124**.

30 [109] Then, at the appropriate time, the sequence manager **148** reads the event and its description from the input-event queue **124**, and, in response to the event, triggers the operation of one or more of the pipelines **74<sub>1</sub>–74<sub>n</sub>** as discussed

above. For example, the sequence manager **148** may trigger the pipeline **74<sub>2</sub>** to begin processing data that the pipeline **74<sub>1</sub>** previously stored in the DPSRAM **104**.

[110] To output an event, the sequence manager **148** generates the event and a description of the event, and loads the event and its description into the 5 output-event queue **130** — the event description identifies the destination peer(s) for the event if there is more than one possible destination peer. For example, as discussed above, the event may confirm the receipt and implementation of an input event, an input-data or input-event message, or a SYNC pulse

[111] Next, the output-data handler **126** retrieves the event and its 10 description from the output-event queue **130**, the subscription manager **138** determines from the event description the destination peer or peers (e.g., the host processor **42** of FIG. 3) of the event, and the output-data handler sends the event to the proper destination peer or peers via the industry-standard bus adapter **118** and the industry-standard bus interface **91** as discussed above.

15 [112] For a configuration command, the industry-standard bus adapter **118** receives the command from the host processor **42** (FIG. 3) via the industry-standard bus interface **91**, and provides the command to the input-data handler **120** in a manner similar to that discussed above for a data-less event (i.e., doorbell)

[113] Next, the validation manager **134** confirms that the command is 20 intended for the pipeline unit **78**, and the input-data handler **120** loads the command into the configuration manager **90**. Furthermore, either the input-data handler **120** or the configuration manager **90** may also pass the command to the output-data handler **126**, which confirms that the pipeline unit **78** received the command by sending the command back to the peer (e.g., the host processor **42** of FIG. 3) that 25 sent the command. This confirmation technique is sometimes called "echoing."

[114] Then, the configuration manager **90** implements the command. For example, the command may cause the configuration manager **90** to disable one of the pipelines **74<sub>1</sub>-74<sub>n</sub>** for debugging purposes. Or, the command may allow a peer, such as the host processor **42** (FIG. 3), to read the current configuration of the 30 pipeline circuit **80** from the configuration manager **90** via the output-data handler

126. In addition, one may use a configuration command to define an exception that is recognized by the exception manager 88.

[115] For an exception, a component, such as the input-data queue 122, of the pipeline circuit 80 triggers an exception to the exception manager 88. In one 5 implementation, the component includes an exception-triggering adapter (not shown) that monitors the component and triggers the exception in response to a predetermined condition or set of conditions. The exception-triggering adapter may be a universal circuit that can be designed once and then included as part of each component of the pipeline circuit 80 that generates exceptions.

10 [116] Next, in response to the exception trigger, the exception manager 88 generates an exception identifier. For example, the identifier may indicate that the input-data queue 122 has overflowed. Furthermore, the identifier may include its destination peer if there is more than one possible destination peer.

[117] Then, the output-data handler 126 retrieves the exception identifier 15 from the exception manager 88 and sends the exception identifier to the host processor 42 (FIG. 3) as discussed in previously cited U.S. Patent App. Serial No. 10/684,053 entitled COMPUTING MACHINE HAVING IMPROVED COMPUTING ARCHITECTURE AND RELATED SYSTEM AND METHOD. Alternatively, if there are multiple possible destination peers, then the exception identifier can also include 20 destination information from which the subscription manager 138 determines the destination peer or peers (e.g., the host processor 42 of FIG. 3) of the identifier. The output-data handler 126 then sends the identifier to the destination peer or peers via the industry-standard bus adapter 118 and the industry-standard bus interface 91.

[118] Still referring to FIG. 5, alternative embodiments to the pipeline unit 78 25 exist. For example, although described as including DPSRAMs, the data memory 92 may include other types of memory ICs such as quad-data-rate (QDR) SRAMs.

[119] FIG. 6 is a block diagram of the interface 142 of FIG. 5 according to an embodiment of the invention. As discussed above in conjunction with FIG. 5, the interface 142 writes processed data from the hardwired pipelines 74<sub>1</sub>-74<sub>n</sub> to the 30 DPSRAM 102. As discussed below, the structure of the interface 142 reduces or

eliminates data "bottlenecks" and, where the pipeline circuit **80** (FIG. 5) is a PLIC, makes efficient use of the PLIC's local and global routing resources.

[120] The interface **142** includes write channels **150<sub>1</sub>** – **150<sub>n</sub>**, one channel for each hardwired pipeline **74<sub>1</sub>** – **74<sub>n</sub>** (FIG. 5), and includes a controller **152**. For 5 purposes of illustration, the channel **150<sub>1</sub>** is discussed below, it being understood that the operation and structure of the other channels **150<sub>2</sub>** – **150<sub>n</sub>** are similar unless stated otherwise.

[121] The channel **150<sub>1</sub>** includes a write-address/data FIFO **154<sub>1</sub>**, and a address/data register **156<sub>1</sub>**.

10 [122] The FIFO **154<sub>1</sub>**, stores the data that the pipeline **74<sub>1</sub>**, writes to the DPSRAM **102**, and stores the address of the location within the DPSRAM **102** to which the pipeline writes the data, until the controller **152** can actually write the data to the DPSRAM **102** via the register **156<sub>1</sub>**. Therefore, the FIFO **154<sub>1</sub>**, reduces or eliminates the data bottleneck that may occur if the pipeline **74<sub>1</sub>**, had to "wait" to write 15 data to the channel **150<sub>1</sub>**, until the controller **152** finished writing previous data.

[123] The FIFO **154<sub>1</sub>**, receives the data from the pipeline **74<sub>1</sub>**, via a bus **158<sub>1</sub>**, receives the address of the location to which the data is to be written via a bus **160<sub>1</sub>**, and provides the data and address to the register **156<sub>1</sub>**, via busses **162<sub>1</sub>** and **164<sub>1</sub>**, respectively. Furthermore, the FIFO **154<sub>1</sub>**, receives a WRITE FIFO signal from the 20 pipeline **74<sub>1</sub>**, on a line **166<sub>1</sub>**, receives a CLOCK signal via a line **168<sub>1</sub>**, and provides a FIFO FULL signal to the pipeline **74<sub>1</sub>**, on a line **170<sub>1</sub>**. In addition, the FIFO **154<sub>1</sub>**, receives a READ FIFO signal from the controller **152** via a line **172<sub>1</sub>**, and provides a FIFO EMPTY signal to the controller via a line **174<sub>1</sub>**. Where the pipeline circuit **80** (FIG. 5) is a PLIC, the busses **158<sub>1</sub>**, **160<sub>1</sub>**, **162<sub>1</sub>**, and **164<sub>1</sub>**, and the lines **166<sub>1</sub>**, **168<sub>1</sub>**, 25 **170<sub>1</sub>**, **172<sub>1</sub>**, and **174<sub>1</sub>**, are preferably formed using local routing resources. Typically, local routing resources are preferred to global routing resources because the signal-path lengths are generally shorter and the routing is easier to implement.

[124] The register **156<sub>1</sub>**, receives the data to be written and the address of the write location from the FIFO **154<sub>1</sub>**, via the busses **162<sub>1</sub>** and **164<sub>1</sub>**, respectively, 30 and provides the data and address to the port **110** of the DPSRAM **102** (FIG. 5) via an address/data bus **176**. Furthermore, the register **156<sub>1</sub>**, also receives the data and

address from the registers  $156_2 - 156_n$ , via an address/data bus  $178_1$  as discussed below. In addition, the register  $156_1$  receives a SHIFT/LOAD signal from the controller  $152$  via a line  $180$ . Where the pipeline circuit  $80$  (FIG. 5) is a PLIC, the bus  $176$  is typically formed using global routing resources, and the busses  $178_1 - 178_{n-1}$  and the line  $180$  are preferably formed using local routing resources.

5 [125] In addition to receiving the FIFO EMPTY signal and generating the READ FIFO and SHIFT/LOAD signals, the controller  $152$  provides a WRITE DPSRAM signal to the port  $110$  of the DPSRAM  $102$  (FIG. 5) via a line  $182$ .

[126] Still referring to FIG. 6, the operation of the interface  $142$  is discussed.

10 [127] First, the FIFO  $154_1$  drives the FIFO FULL signal to the logic level corresponding to the current state ("full" or "not full") of the FIFO.

15 [128] Next, if the FIFO  $154_1$  is not full and the pipeline  $74_1$  has processed data to write, the pipeline drives the data and corresponding address onto the busses  $158_1$  and  $160_1$ , respectively, and asserts the WRITE signal, thus loading the data and address into the FIFO. If the FIFO  $154_1$  is full, however, the pipeline  $74_1$  waits until the FIFO is not full before loading the data.

[129] Then, the FIFO  $154_1$  drives the FIFO EMPTY signal to the logic level corresponding to the current state ("empty" or "not empty") of the FIFO.

20 [130] Next, if the FIFO  $154_1$  is not empty, the controller  $152$  asserts the READ FIFO signal and drives the SHIFT/LOAD signal to the load logic level, thus loading the first loaded data and address from the FIFO into the register  $156_1$ . If the FIFO  $154_1$  is empty, the controller  $152$  does not assert READ FIFO, but does drive SHIFT load to the load logic level if any of the other FIFOs  $154_2 - 154_n$  are not empty.

25 [131] The channels  $150_2 - 150_n$  operate in a similar manner such that first-loaded data in the FIFOs  $154_2 - 154_n$  are respectively loaded into the registers  $156_2 - 156_n$ .

[132] Then, the controller  $152$  drives the SHIFT/LOAD signal to the shift logic level and asserts the WRITE DPSRAM signal, thus serially shifting the data and addresses from the registers  $156_1 - 156_n$  onto the address/data bus  $176$  and loading 30 the data into the corresponding locations of the DPSRAM  $102$ . Specifically, during a

first shift cycle, the data and address from the register **156<sub>1</sub>**, are shifted onto the bus **176** such that the data from the FIFO **154<sub>1</sub>**, is loaded into the addressed location of the DPSRAM **102**. Also during the first shift cycle, the data and address from the register **156<sub>2</sub>** are shifted into the register **156<sub>1</sub>**, the data and address from the 5 register **156<sub>3</sub>** (not shown) are shifted into the register **156<sub>2</sub>**, and so on. During a second shift cycle, the data and address from the register **156<sub>1</sub>** are shifted onto the bus **176** such that the data from the FIFO **154<sub>2</sub>** is loaded into the addressed location of the DPSRAM **102**. Also during the second shift cycle, the data and address from the register **156<sub>2</sub>** are shifted into the register **156<sub>1</sub>**, the data and address from the 10 register **156<sub>3</sub>** (not shown) are shifted into the register **156<sub>2</sub>**, and so on. There are n shift cycles, and during the nth shift cycle the data and address from the register **156<sub>n</sub>** (which is the data and address from the FIFO **154<sub>n</sub>**) is shifted onto the bus **176**. The controller **152** may implement these shift cycles by pulsing the SHIFT/LOAD signal, or by generating a shift clock signal (not shown) that is coupled to the 15 registers **156<sub>1</sub>-156<sub>n</sub>**. Furthermore, if one of the registers **156<sub>1</sub>-156<sub>n</sub>** is empty during a particular shift operation because its corresponding FIFO **154<sub>1</sub>-154<sub>n</sub>** was empty when the controller **152** loaded the register, then the controller may bypass the empty register, and thus shorten the shift operation by avoiding shifting null data and a null address onto the bus **176**.

20 [133] Referring to FIGS. 5 and 6, according to an embodiment of the invention, the interface **144** is similar to the interface **142**, and the interface **132** is also similar to the interface **142** except that the interface **132** includes only one write channel **150**.

25 [134] FIG. 7 is a block diagram of the interface **140** of FIG. 5 according to an embodiment of the invention. As discussed above in conjunction with FIG. 5, the interface **140** reads input data from the DPSRAM **100** and transfers this data to the hardwired **74<sub>1</sub>-74<sub>n</sub>**. As discussed below, the structure of the interface **140** reduces or eliminates data "bottlenecks" and, where the pipeline circuit **80** (FIG. 5) is a PLIC, makes efficient use of the PLIC's local and global routing resources.

30 [135] The interface **140** includes read channels **190<sub>1</sub> - 190<sub>n</sub>**, one channel for each hardwired pipeline **74<sub>1</sub> - 74<sub>n</sub>** (FIG. 5), and a controller **192**. For purposes of illustration, the read channel **190<sub>1</sub>** is discussed below, it being understood that the

operation and structure of the other read channels  $190_2 - 190_n$  are similar unless stated otherwise.

[136] The channel  $190_1$  includes a FIFO  $194_1$  and an address/identifier (ID) register  $196_1$ . As discussed below, the identifier identifies the pipeline  $74_1-74_n$  that makes the request to read data from a particular location of the DPSRAM  $100$  to receive the data.

[137] The FIFO  $194_1$  includes two sub-FIFOs (not shown), one for storing the address of the location within the DPSRAM  $100$  from which the pipeline  $74_1$  wishes to read the input data, and the other for storing the data read from the DPSRAM  $100$ . Therefore, the FIFO  $194_1$  reduces or eliminates the bottleneck that may occur if the pipeline  $74_1$  had to "wait" to provide the read address to the channel  $190_1$ , until the controller  $192$  finished reading previous data, or if the controller had to wait until the pipeline  $74_1$  retrieved the read data before the controller could read subsequent data.

[138] The FIFO  $194_1$  receives the read address from the pipeline  $74_1$  via a bus  $198_1$  and provides the address and ID to the register  $196_1$  via a bus  $200_1$ . Since the ID corresponds to the pipeline  $74_1$  and typically does not change, the FIFO  $194_1$  may store the ID and concatenate the ID with the address. Alternatively, the pipeline  $74_1$  may provide the ID to the FIFO  $194_1$  via the bus  $198_1$ . Furthermore, the FIFO  $194_1$  receives a READY WRITE FIFO signal from the pipeline  $74_1$  via a line  $202_1$ , receives a CLOCK signal via a line  $204_1$ , and provides a FIFO FULL (of read addresses) signal to the pipeline via a line  $206_1$ . In addition, the FIFO  $194_1$  receives a WRITE/READ FIFO signal from the controller  $192$  via a line  $208_1$ , and provides a FIFO EMPTY signal to the controller via a line  $210_1$ . Moreover, the FIFO  $194_1$  receives the read data and the corresponding ID from the controller  $192$  via a bus  $212$ , and provides this data to the pipeline  $74_1$  via a bus  $214_1$ . Where the pipeline circuit  $80$  (FIG. 5) is a PLIC, the busses  $198_1$ ,  $200_1$ , and  $214_1$  and the lines  $202_1$ ,  $204_1$ ,  $206_1$ ,  $208_1$ , and  $210_1$  are preferably formed using local routing resources, and the bus  $212$  is typically formed using global routing resources.

[139] The register  $196_1$  receives the address of the location to be read and the corresponding ID from the FIFO  $194_1$  via the bus  $206_1$ , provides the address to the port  $108$  of the DPSRAM  $100$  (FIG. 5) via an address bus  $216$ , and provides the

ID to the controller **192** via a bus **218**. Furthermore, the register **196<sub>i</sub>** also receives the addresses and IDs from the registers **196<sub>2</sub> – 196<sub>n</sub>** via an address/ID bus **220<sub>i</sub>**, as discussed below. In addition, the register **196<sub>i</sub>** receives a SHIFT/LOAD signal from the controller **192** via a line **222**. Where the pipeline circuit **80** (FIG. 5) is a PLIC, the bus **216** is typically formed using global routing resources, and the busses **220<sub>i</sub>, 220<sub>n-1</sub>** and the line **222** are preferably formed using local routing resources.

5 [140] In addition to receiving the FIFO EMPTY signal, generating the WRITE/READ FIFO and SHIFT/LOAD signals, and providing the read data and corresponding ID, the controller **192** receives the data read from the port **108** of the DPSRAM **100** (FIG. 5) via a bus **224** and generates a READ DPSRAM signal on a line **226**, which couples this signal to the port **108**. Where the pipeline circuit **80** (FIG. 5) is a PLIC, the bus **224** and the line **226** are typically formed using global routing resources.

10 [141] Still referring to FIG. 7, the operation of the interface **140** is discussed.  
15 [142] First, the FIFO **194<sub>i</sub>** drives the FIFO FULL signal to the logic level corresponding to the current state ("full" or "not full") of the FIFO relative to the read addresses. That is, if the FIFO **194<sub>i</sub>** is full of addresses to be read, then it drives the logic level of FIFO FULL to one level, and if the FIFO is not full of read addresses, it drives the logic level of FIFO FULL to another level.  
20 [143] Next, if the FIFO **194<sub>i</sub>** is not full of read addresses and the pipeline **74<sub>i</sub>** is ready for more input data to process, the pipeline drives the address of the data to be read onto the bus **198<sub>i</sub>**, and asserts the READ/WRITE FIFO signal to a write level, thus loading the address into the FIFO. As discussed above in conjunction with FIG. 5, the pipeline **74<sub>i</sub>** gets the address from the input-data queue **122** via the sequence manager **148**. If, however, the FIFO **194<sub>i</sub>** is full of read addresses, the pipeline **74<sub>i</sub>** waits until the FIFO is not full before loading the read address.  
25

30 [144] Then, the FIFO **194<sub>i</sub>** drives the FIFO EMPTY signal to the logic level corresponding to the current state ("empty" or "not empty") of the FIFO relative to the read addresses. That is, if the FIFO **194<sub>i</sub>** is loaded with at least one read address, it drives the logic level of FIFO EMPTY to one level, and if the FIFO is loaded with no read addresses, it drives the logic level of FIFO EMPTY to another level.

- [145] Next, if the FIFO  $194_1$  is not empty, the controller  $192$  asserts the WRITE/READ FIFO signal to the read logic level and drives the SHIFT/LOAD signal to the load logic level, thus loading the first loaded address and the ID from the FIFO into the register  $196_1$ .
- 5 [146] The channels  $190_2 - 190_n$  operate in a similar manner such that the controller  $192$  respectively loads the first-loaded addresses and IDs from the FIFOs  $194_2 - 194_n$  into the registers  $196_2 - 196_n$ . If all of the FIFOs  $194_2 - 194_n$  are empty, then the controller  $192$  waits for at least one of the FIFOs to receive an address before proceeding.
- 10 [147] Then, the controller  $192$  drives the SHIFT/LOAD signal to the shift logic level and asserts the READ DPSRAM signal to serially shift the addresses and IDs from the registers  $196_1 - 196_n$  onto the address and ID busses  $216$  and  $218$  and to serially read the data from the corresponding locations of the DPSRAM  $100$  via the bus  $224$ .
- 15 [148] Next, the controller  $192$  drives the received data and corresponding ID — the ID allows each of the FIFOs  $194_1 - 194_n$  to determine whether it is an intended recipient of the data — onto the bus  $212$ , and drives the WRITE/READ FIFO signal to a write level, thus serially writing the data to the respective FIFO,  $194_1 - 194_n$ .
- 20 [149] Then, the hardwired pipelines  $74_1 - 74_n$  sequentially assert their READ/WRITE FIFO signals to a read level and sequentially read the data via the busses  $214_1 - 214_n$ .
- [150] Still referring to FIG. 7, a more detailed discussion of their data-read operator is presented.
- 25 [151] During a first shift cycle, the controller  $192$  shifts the address and ID from the register  $196_1$  onto the busses  $216$  and  $218$ , respectively, asserts read DPSRAM, and thus reads the data from the corresponding location of the DPSRAM  $100$  via the bus  $224$  and reads the ID from the bus  $218$ . Next, the controller  $192$  drives WRITE/READ FIFO signal on the line  $208_1$  to a write level and drives the received data and the ID onto the bus  $212$ . Because the ID is the ID from the FIFO  $194_1$ , the FIFO  $194_1$  recognizes the ID and thus loads the data from the bus  $212$  in

- response the write level of the WRITE/READ FIFO signal. The remaining FIFOs  $194_2 - 194_n$  do not load the data because the ID on the bus  $212$  does not correspond to their IDs. Then, the pipeline  $74_1$  asserts the READ/WRITE FIFO signal on the line  $202_1$  to the read level and retrieves the read data via the bus  $214_1$ .
- 5 Also during the first shift cycle, the address and ID from the register  $196_2$  are shifted into the register  $196_1$ , the address and ID from the register  $196_3$  (not shown) are shifted into the register  $196_2$ , and so on. Alternatively, the controller  $192$  may recognize the ID and drive only the WRITE/READ FIFO signal on the line  $208_1$  to the write level. This eliminates the need for the controller  $192$  to send the ID to the
- 10 FIFOs  $194_1 - 194_n$ . In another alternative, the WRITE/READ FIFO signal may be only a read signal, and the FIFO  $194_1$  (as well as the other FIFOs  $194_2 - 194_n$ ) may load the data on the bus  $212$  when the ID on the bus  $212$  matches the ID of the FIFO  $194_1$ . This eliminates the need of the controller  $192$  to generate a write signal.

[152] During a second shift cycle, the address and ID from the register  $196_1$  is shifted onto the busses  $216$  and  $218$  such that the controller  $192$  reads data from the location of the DPSRAM  $100$  specified by the FIFO  $194_2$ . Next, the controller  $192$  drives the WRITE/READ FIFO signal to a write level and drives the received data and the ID onto the bus  $212$ . Because the ID is the ID from the FIFO  $194_2$ , the FIFO  $194_2$  recognizes the ID and thus loads the data from the bus  $212$ . The remaining FIFOs  $194_1$  and  $194_3 - 194_n$  do not load the data because the ID on the bus  $212$  does not correspond to their IDs. Then, the pipeline  $74_2$  asserts its READ/WRITE FIFO signal to the read level and retrieves the read data via the bus  $214_2$ . Also during the second shift cycle, the address and ID from the register  $196_2$  is shifted into the register  $196_1$ , the address and ID from the register  $196_3$  (not shown) is shifted into the register  $196_2$ , and so on.

[153] This continues for  $n$  shift cycles, i.e., until the address and ID from the register  $196_n$  (which is the address and ID from the FIFO  $194_n$ ) are respectively shifted onto the bus  $216$  and  $218$ . The controller  $192$  may implement these shift cycles by pulsing the SHIFT/LOAD signal, or by generating a shift clock signal (not shown) that is coupled to the registers  $196_1 - 196_n$ . Furthermore, if one of the registers  $196_1 - 196_2$  is empty during a particular shift operation because its corresponding FIFO  $194_1 - 194_n$  is empty, then the controller  $192$  may bypass the

empty register, and thus shorten the shift operation by avoiding shifting a null address onto the bus 216.

[154] Referring to FIGS. 5 and 6, according to an embodiment of the invention, the interface 144 is similar to the interface 140, and the interface 136 is also similar to the interface 140 except that the interface 136 includes only one read channel 190, and thus includes no ID circuitry.

[155] Fig. 8 is a schematic block diagram of a pipeline unit 230 of FIG. 4 according to another embodiment of the invention. The pipeline unit 230 is similar to the pipeline unit 78 of FIG. 4 except that the pipeline unit 230 includes multiple pipeline circuits 80 — here two pipeline circuits 80a and 80b. Increasing the number of pipeline circuits 80 typically allows an increase in the number n of hardwired pipelines 74<sub>1</sub>-74<sub>n</sub>, and thus an increase in the functionality of the pipeline unit 230 as compared to the pipeline unit 78.

[156] In the pipeline unit 230 of FIG. 8, the services components, i.e., the communication interface 82, the controller 86, the exception manager 88, the configuration manager 90, and the optional industry-standard bus interface 91, are disposed on the pipeline circuit 80a, and the pipelines 74<sub>1</sub>-74<sub>n</sub> and the communication shell 84 are disposed on the pipeline circuit 80b. By locating the services components and the pipelines 74<sub>1</sub>-74<sub>n</sub> on separate pipeline circuits, one can include a higher number n of pipelines and/or more complex pipelines than he can where the service components and the pipelines are located on the same pipeline circuit. Alternatively, the portion of the communication shell 84 that interfaces the pipelines 74<sub>1</sub>-74<sub>n</sub> to the interface 82 and the controller 86 may be disposed on the pipeline circuit 80a.

[157] FIG. 9 is a schematic block diagram of the pipeline circuits 80a and 80b and the data memory 92 of the pipeline unit 230 of FIG. 8 according to an embodiment of the invention. Other than the pipeline components being disposed on two pipelines circuits, the structure and operation of the pipeline circuits 80a and 80b and the memory 92 of FIG. 9 are the same as for the pipeline circuit 80 and memory 92 of FIG. 5.

[158] The preceding discussion is presented to enable a person skilled in the art to make and use the invention. Various modifications to the embodiments will be readily apparent to those skilled in the art, and the generic principles herein may be applied to other embodiments and applications without departing from the spirit and 5 scope of the present invention. Thus, the present invention is not intended to be limited to the embodiments shown, but is to be accorded the widest scope consistent with the principles and features disclosed herein.

**WHAT IS CLAIMED IS:**

1. A pipeline accelerator, comprising:
  - a memory; and
  - a hardwired-pipeline circuit coupled to the memory and operable to,
    - 5 receive data,
    - load the data into the memory,
    - retrieve the data from the memory,
    - process the retrieved data, and
    - provide the processed data to an external source.
2. The pipeline accelerator of claim 1 wherein:  
the memory is disposed on a first integrated circuit; and  
the pipeline circuit is disposed on a second integrated circuit.
3. The pipeline accelerator of claim 1 wherein the pipeline circuit is disposed on a field-programmable gate array.
4. The pipeline accelerator of claim 1 wherein the pipeline circuit is operable to provide the processed data to the external source by:  
loading the processed data into the memory;  
retrieving the processed data from the memory; and  
providing the retrieved processed data to the external source.
5. The pipeline accelerator of claim 1 wherein:  
the external source comprises a processor; and  
the pipeline circuit is operable to receive the data from the processor.
6. A computing machine, comprising:  
a processor; and  
a pipeline accelerator coupled to the processor and comprising,
  - a memory, and
  - a hardwired-pipeline circuit coupled to the memory and operable to,
    - receive data from the processor,
    - load the data into the memory,
    - retrieve the data from the memory,
    - process the retrieved data, and

provide the processed data to the processor.

7. A pipeline accelerator, comprising:  
a memory; and  
a hardwired-pipeline circuit coupled to the memory and operable to,  
receive data,  
process the received data,  
load the processed data into the memory,  
retrieve the processed data from the memory, and  
provide the retrieved processed data to an external source.
8. A computing machine, comprising:  
a processor; and  
a pipeline accelerator coupled to the processor and comprising,  
a memory, and  
a hardwired-pipeline circuit coupled to the memory and operable to,  
receive data from the processor,  
process the received data,  
load the processed data into the memory,  
retrieve the processed data from the memory, and  
provide the retrieved processed data to the processor.
9. A pipeline accelerator, comprising:  
first and second memories; and  
a hardwired-pipeline circuit coupled to the first and second memories and  
comprising,  
an input-data handler operable to receive raw data from an external  
source and to load the raw data into the first memory,  
a hardwired pipeline operable to process the raw data,  
a pipeline interface operable to retrieve the raw data from the first  
memory, provide the retrieved raw data to the hardwired pipeline, and load  
processed data from the hardwired pipeline into the second memory, and  
an output-data handler operable to retrieve the processed data from  
the second memory and to provide the processed data to the external source.

10. The pipeline accelerator of claim 9 wherein:

the first and second memories each include respective first and second ports; the input-data handler is operable to load the raw data via the first port of the first memory,

the pipeline interface is operable to retrieve the raw data via the second port of the first memory and to load the processed data via the first port of the second memory, and

the output-data handler is operable to retrieve the processed data via the second port of the second memory.

11. The pipeline accelerator of claim 9, further comprising:  
a third memory coupled to the hardwired-pipeline circuit;  
wherein the hardwired pipeline is operable to generate intermediate data while processing the raw data; and  
wherein the pipeline interface is operable to load the intermediate data into the third memory and to retrieve the intermediate data from the third memory.

12. The pipeline accelerator of claim 9 wherein:  
the first and second memories are respectively disposed on first and second integrated circuits; and  
the pipeline circuit is disposed on a field-programmable gate array.

13. The pipeline accelerator of claim 9, further comprising:  
an input-data queue coupled to the input-data handler and the pipeline interface;  
wherein the input-data handler is operable to load into the input-data queue a pointer to a location of the raw data within the first memory; and  
wherein the pipeline interface is operable to retrieve the raw data from the location using the pointer.

14. The pipeline accelerator of claim 9, further comprising:  
an output-data queue coupled to the output-data handler and the pipeline interface;  
wherein the pipeline interface is operable to load into the output-data queue a pointer to a location of the processed data within the second memory; and  
wherein the output-data handler is operable to retrieve the processed data from the location using the pointer.

15. The pipeline accelerator of claim 9, further comprising:  
wherein each of the input-data handler, hardwired pipeline, pipeline interface, and output-data handler has a respective operating configuration; and  
a configuration manager coupled to and operable to set the operating configurations of the input-data handler, hardwired pipeline, pipeline interface, and output-data handler.

16. The pipeline accelerator of claim 9, further comprising:  
wherein each of the input-data handler, hardwired pipeline, pipeline interface, and output-data handler has a respective operating status; and  
an exception manager coupled to and operable to identify an exception in the input-data handler, hardwired pipeline, pipeline interface, or output-data handler in response to the operating statuses.

17. A pipeline accelerator, comprising:  
a hardwired pipeline operable to process data; and  
an input-data handler coupled to the hardwired pipeline and operable to,  
receive the data,  
determine whether the data is directed to the hardwired pipeline, and  
provide the data to the hardwired pipeline if the data is directed to the hardwired pipeline.

18. The pipeline accelerator of claim 17 wherein the input-data handler is further operable to:

receive the data by,  
receiving a message that includes a header and the data, and  
extracting the data from the message; and  
determine whether the data is directed to the hardwired pipeline by analyzing the header.

19. The pipeline accelerator of claim 17 wherein the hardwired pipeline and the input-data handler are disposed on a single field-programmable gate array.

20. The pipeline accelerator of claim 17 wherein the hardwired pipeline and the input-data handler are disposed on respective field-programmable gate arrays.

21. A computing machine, comprising:
  - a processor; and
  - a pipeline accelerator coupled to the processor and comprising:
    - a hardwired pipeline operable to process data, and
    - an input-data handler coupled to the hardwired pipeline and operable to,
      - receive the data from the processor,
      - determine whether the data is directed to the hardwired pipeline, and
      - provide the data to the hardwired pipeline if the data is directed to the hardwired pipeline.
22. A pipeline accelerator, comprising:
  - a hardwired pipeline operable to generate data; and
  - an output-data handler coupled to the hardwired pipeline and operable to,
    - receive the data,
    - determine a destination of the data, and
    - provide the data to the destination.
23. The pipeline accelerator of claim 22 wherein the output-data handler is further operable to:
  - determine the destination of the data by,
    - identifying a type of the data, and
    - determining the destination based on the type of the data; and
  - provide the data to the destination by,
    - generating a message that identifies the destination and that includes the data, and
    - providing the message to the destination.
24. A computing machine, comprising:
  - a processor operable to execute threads of an application; and
  - a pipeline accelerator coupled to the processor and comprising:
    - a hardwired pipeline operable to generate data, and
    - an output-data handler coupled to the hardwired pipeline and operable to,

receive the data,

identify a thread of the application that subscribes to the data,

and

provide the data to the subscribing thread.

25. A pipeline accelerator, comprising:

a hardwired pipeline operable to process data values; and

a sequence manager coupled to and operable to control the operation of the hardwired pipeline.

26. The pipeline accelerator of claim 25 wherein the sequence manager is operable to control an order in which the hardwired pipeline receives the data values.

27. The pipeline accelerator of claim 25 wherein the sequence manager is further operable to:

receive an event; and

control the hardwired pipeline in response to the event.

28. The pipeline accelerator of claim 25 wherein the sequence manager is further operable to:

receive a synchronization signal; and

control the operation of the hardwired pipeline in response to the synchronization signal.

29. The pipeline accelerator of claim 25 wherein the sequence manager is further operable to:

sense an occurrence relative to the hardwired pipeline; and

generate an event in response to the occurrence.

30. A computing machine, comprising:

a processor operable to generate data and an event; and

a pipeline accelerator coupled to the processor and comprising,

a hardwired pipeline operable to receive the data from the processor and process the received data; and

a sequence manager coupled to the hardwired pipeline and operable to receive the event from the processor and to control the operation of the hardwired pipeline in response to the event.

31. A pipeline accelerator, comprising:

a hardwired-pipeline circuit having an operating configuration and operable to process data; and

a configuration manager coupled to the hardwired-pipeline circuit and operable to set the operating configuration.

32. The pipeline accelerator of claim 31 wherein:

the hardwired-pipeline circuit includes a configuration register; and

the configuration manager is operable to set the operating configuration by loading a configuration value into the configuration register.

33. The pipeline accelerator of claim 32 wherein the configuration manager is operable to receive the configuration value from an external source.

34. A computing machine, comprising:

a processor operable to generate data and a configuration value; and  
pipeline accelerator coupled to the processor and comprising,

a hardwired-pipeline circuit having an operating configuration and operable to process the data, and

a configuration manager coupled to the hardwired-pipeline circuit and operable to set the operating configuration in response to the configuration value.

35. A pipeline accelerator, comprising:

a hardwired-pipeline circuit having an operating status and operable to process data; and

an exception manager coupled to the hardwired-pipeline circuit and operable to identify an exception in the operation status of the hardwired-pipeline circuit in response to the operating status.

36. The pipeline accelerator of claim 35 wherein:

the hardwired-pipeline circuit is operable to generate a status value that represents the operating status; and

the exception manager is operable to identify the exception in response to the status value.

37. The pipeline accelerator of claim 36 wherein:

the hardwired-pipeline circuit includes a status register that is operable to store the status value; and

the exception manager receives the status value from the status register.

38. The pipeline accelerator of claim 35 wherein the exception manager is operable to identify an exception in the operating status of the hardwired-pipeline circuit to an external source.

39. A computing machine, comprising:

a processor operable to generate data; and

a pipeline accelerator, comprising,

a hardwired-pipeline circuit having an operating status and operable to process data and to generate a status value that represents the operating status, and

an exception manager coupled to the hardwired-pipeline circuit and operable to identify an exception in the operating status of the hardwired-pipeline circuit in response to the status value and to notify the processor of the exception.

40. A computing machine, comprising:

a pipeline accelerator, comprising,

a hardwired-pipeline circuit having an operating status and operable to process data, and

an exception manager coupled to the hardwired-pipeline circuit and operable to generate a status value that represents the operating status; and

a processor coupled to the pipeline accelerator and operable to generate the data, to receive the status value, and to determine whether the hardwired-pipeline circuit is malfunctioning by analyzing the status value.

41. A method, comprising:

loading data into a memory;

retrieving the data from the memory;

processing the retrieved data with a hardwired-pipeline circuit; and

providing the processed data to an external source.

42. The method of claim 41 wherein providing the processed data comprises:

loading the processed data into the memory;  
retrieving the processed data from the memory; and  
providing the retrieved processed data to the external source.

43. A method, comprising:

processing data with a hardwired-pipeline circuit;  
loading the processed data into a memory;  
retrieving the processed data from the memory; and  
providing the retrieved processed data to an external source.

44. A method, comprising:

loading raw data from an external source into a first memory;  
retrieving the raw data from the first memory;  
processing the retrieved data with a hardwired pipeline;  
loading the processed data from the hardwired pipeline into a second memory; and  
providing the processed data from the second memory to the external source.

45. The method of claim 44 wherein:

loading the raw data comprises loading the raw data via a first port of the first memory;

retrieving the raw data comprises retrieving the raw data via a second port of the first memory;

loading the processed data comprises loading the processed data via a first port of the second memory; and

providing the processed data comprises retrieving the processed data via a second port of the second memory.

46. The method of claim 44, further comprising:

generating intermediate data with the hardwired pipeline in response to processing the raw data;

loading the intermediate data into a third memory; and

providing the intermediate data from the third memory back to the hardwired pipeline.

47. The method of claim 44, further comprising:  
loading into an input-message queue a pointer to a location of the raw data within the first memory; and  
wherein retrieving the raw data comprises retrieving the raw data from the location using the pointer.

48. The method of claim 44, further comprising:  
loading into an output-message queue a pointer to a location of the processed data within the second memory; and  
wherein retrieving the processed data comprises retrieving the processed data from the location using the pointer.

49. The method of claim 44, further comprising setting parameters for loading and retrieving the raw data, processing the retrieved data, and loading and providing the processed data.

50. The method of claim 44, further comprising determining whether an error occurs during the loading and retrieving of the raw data, the processing of the retrieved data, and the loading and providing of the processed data.

51. A method, comprising:  
receiving data;  
determining whether the data is directed to a hardwired pipeline; and  
providing the data to the hardwired pipeline if the data is directed to the hardwired pipeline.

52. The method of claim 51 wherein:  
receiving the data comprises,  
receiving a message that includes a header and the data, and  
extracting the data from the message; and  
determining whether the data is directed to the hardwired pipeline comprises analyzing the header.

53. A method, comprising:  
generating data with a hardwired pipeline;

determining a destination of the data; and  
providing the data to the destination.

54. The method of claim 53 wherein:  
determining the destination of the data comprises,  
identifying a type of the data, and  
determining the destination based on the type of the data; and  
providing the data to the destination comprises,  
generating a message that identifies the destination and that includes  
the data, and  
providing the message to the destination.

55. A method, comprising:  
processing data values with a hardwired pipeline; and  
sequencing the operation of the hardwired pipeline.

56. The method of claim 55 wherein sequencing the operation comprises  
sequencing an order in which the hardwired pipeline processes the data values.

57. The method of claim 55 wherein sequencing the operating comprises  
synchronizing the operation of the hardwired pipeline to a synchronization signal.

58. The method of claim 55, further comprising:  
sensing a predefined occurrence during operation of the hardwired pipeline;  
and  
generating an event in response to the occurrence.

59. A method, comprising:  
loading a configuration value into a register; and  
setting an operating configuration of a hardwired pipeline with the  
configuration value.

60. A method, comprising:  
processing data with a hardwired pipeline; and  
identifying an error in the processed data by analyzing an operating status of  
the hardwired pipeline.

61. A method for designing a hardwired-pipeline circuit, comprising:

retrieving from a library a first data representation of a communication interface;

generating a second data representation of a hardwired pipeline that is to be coupled to the communication interface; and

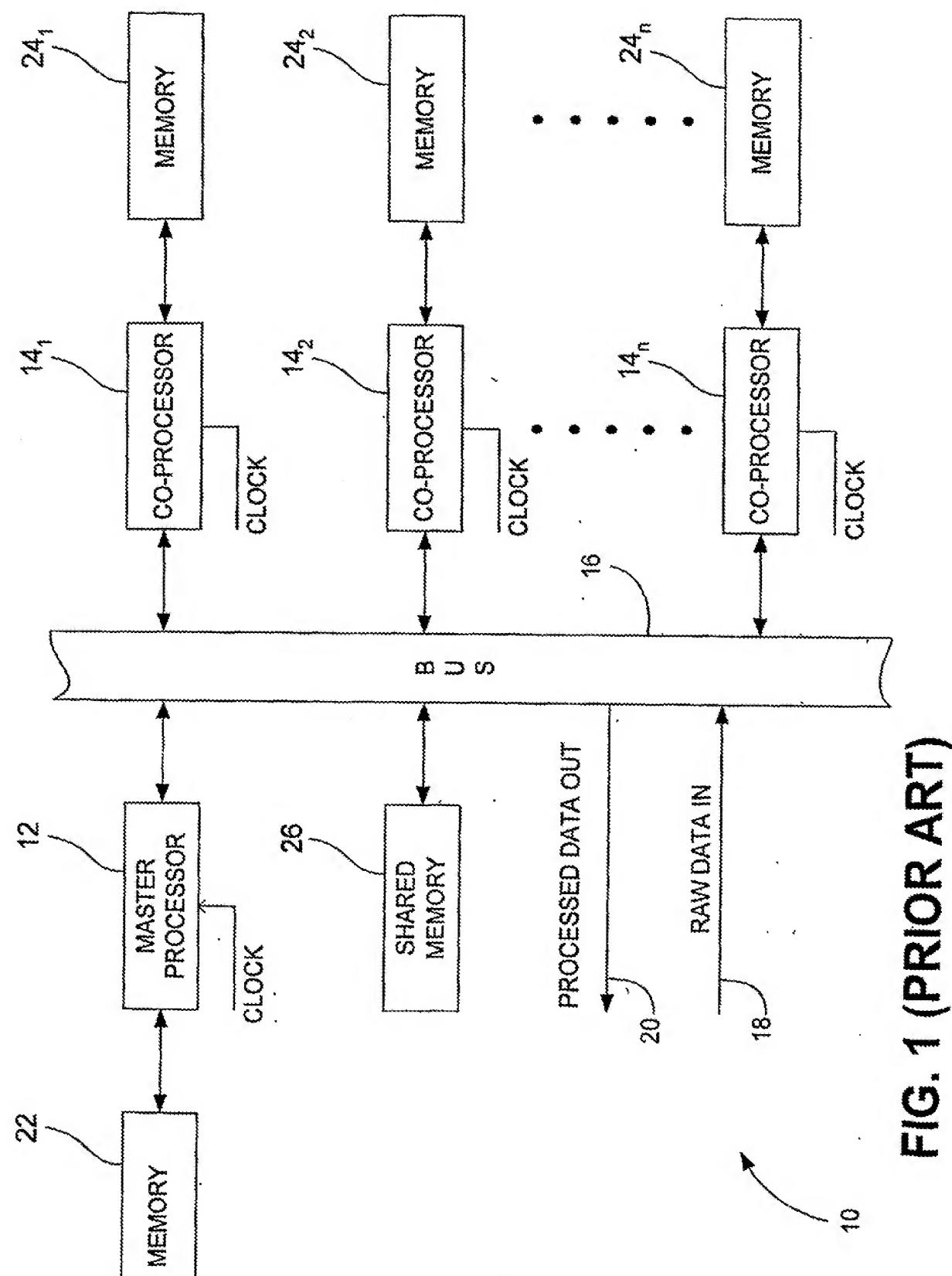
combining the first and second data representations to generate hard-configuration data for the hardwired-pipeline circuit.

62. The method of claim 61, further comprising modifying the first data representation by selecting values for predetermined parameters of the services layer before combining the first and second data representations.

63. The method of claim 61 wherein the communication interface is operable to allow the hardwired-pipeline circuit to communicate with another circuit.

64. The method of claim 61 wherein combining the first and second data representations comprises compiling the first and second data representations into the hard-configuration data.

65. The method of claim 61 wherein the hard-configuration data comprises firmware.

**FIG. 1 (PRIOR ART)**

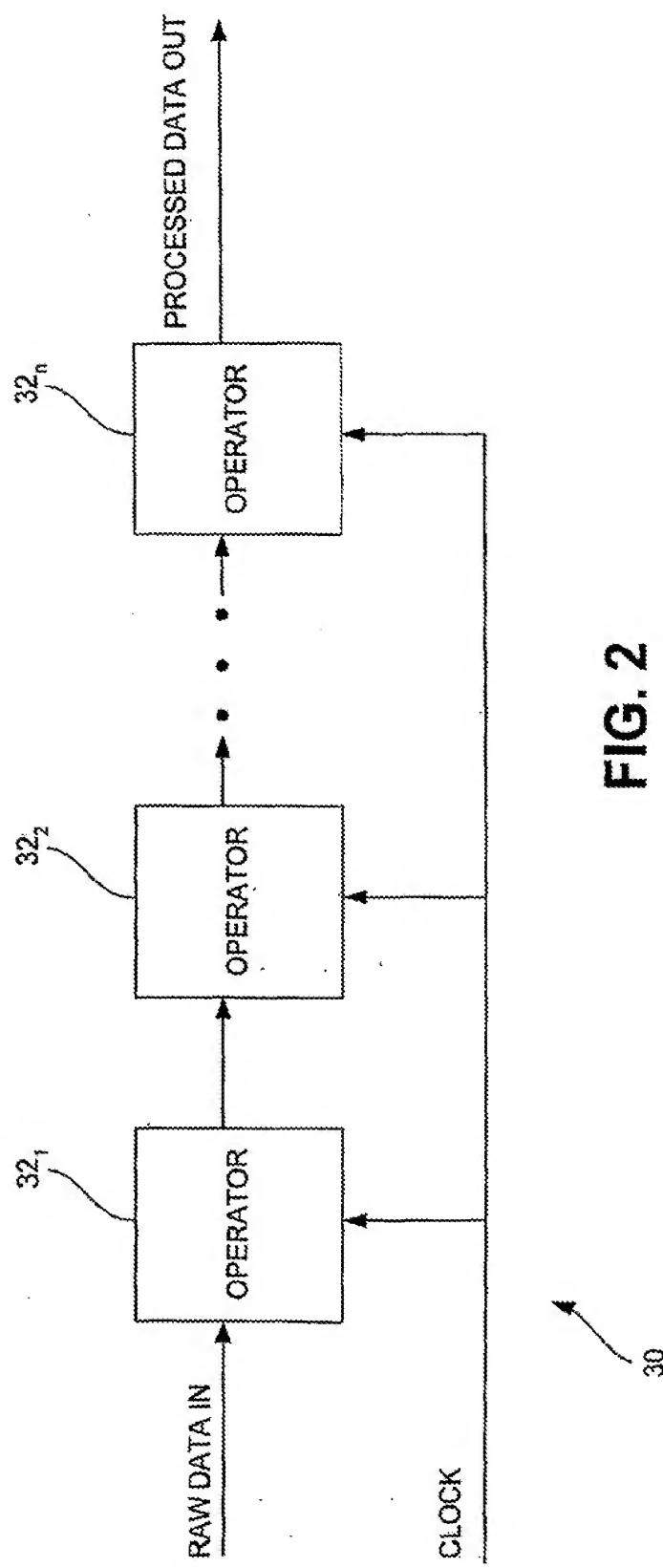
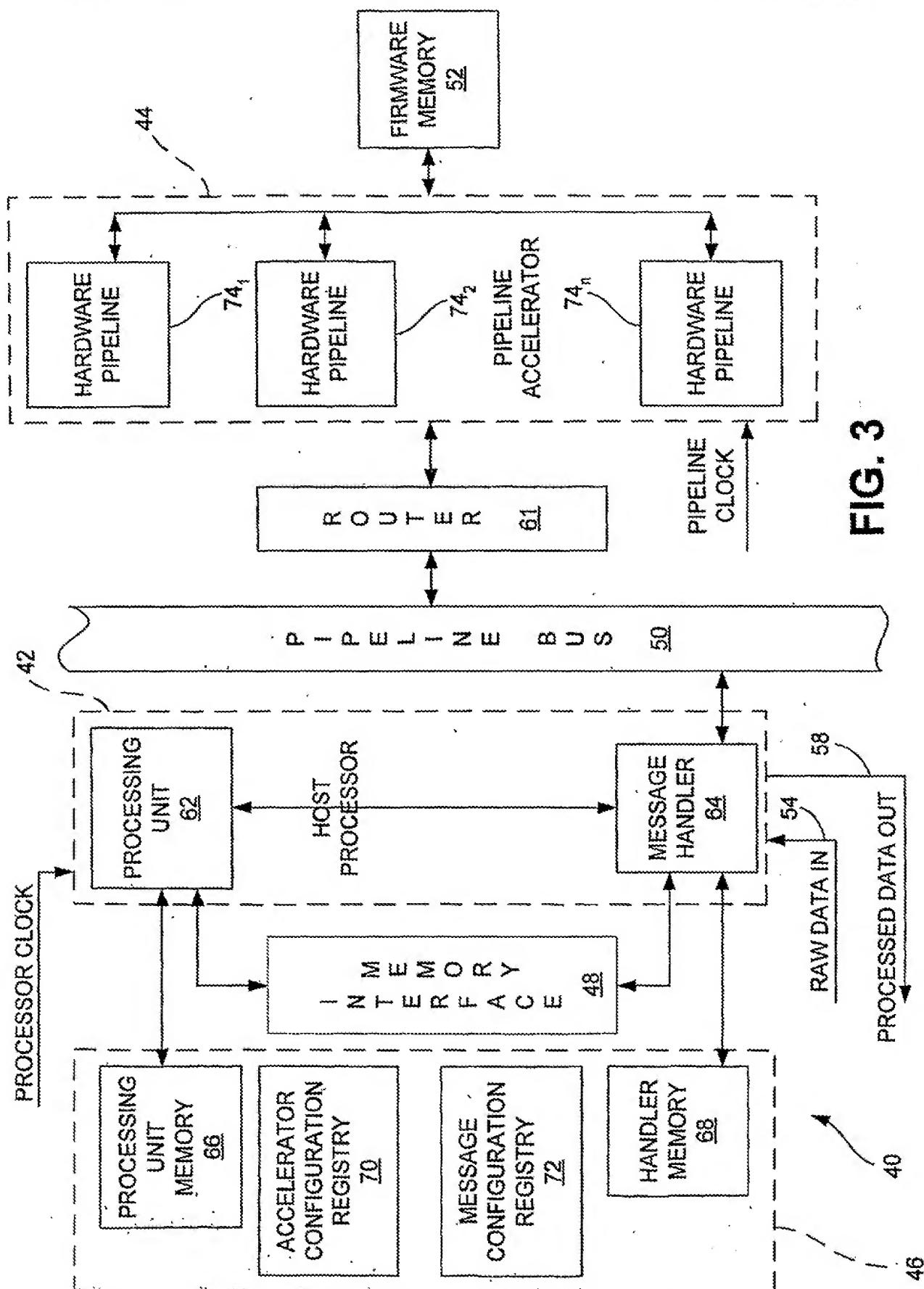
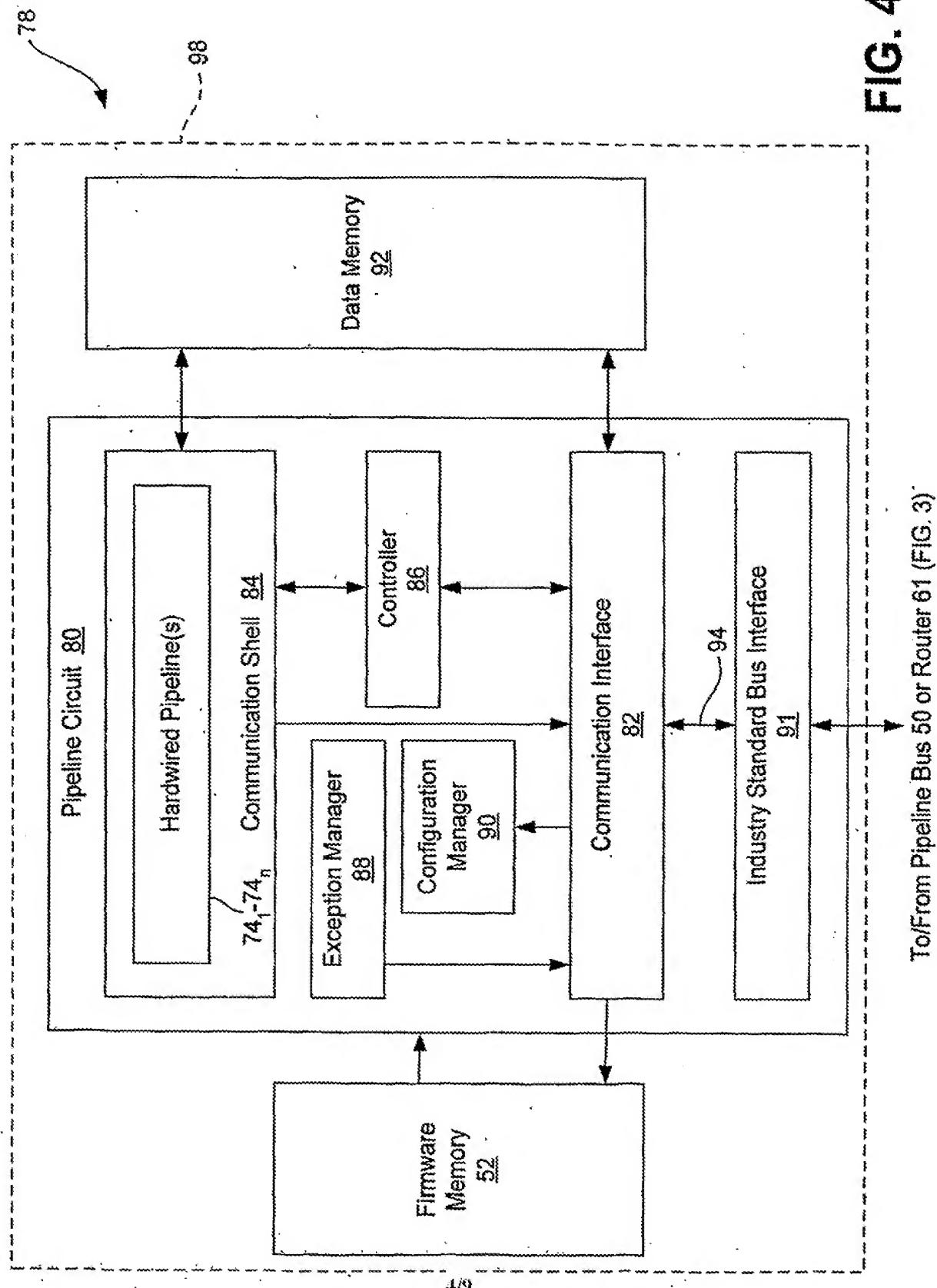
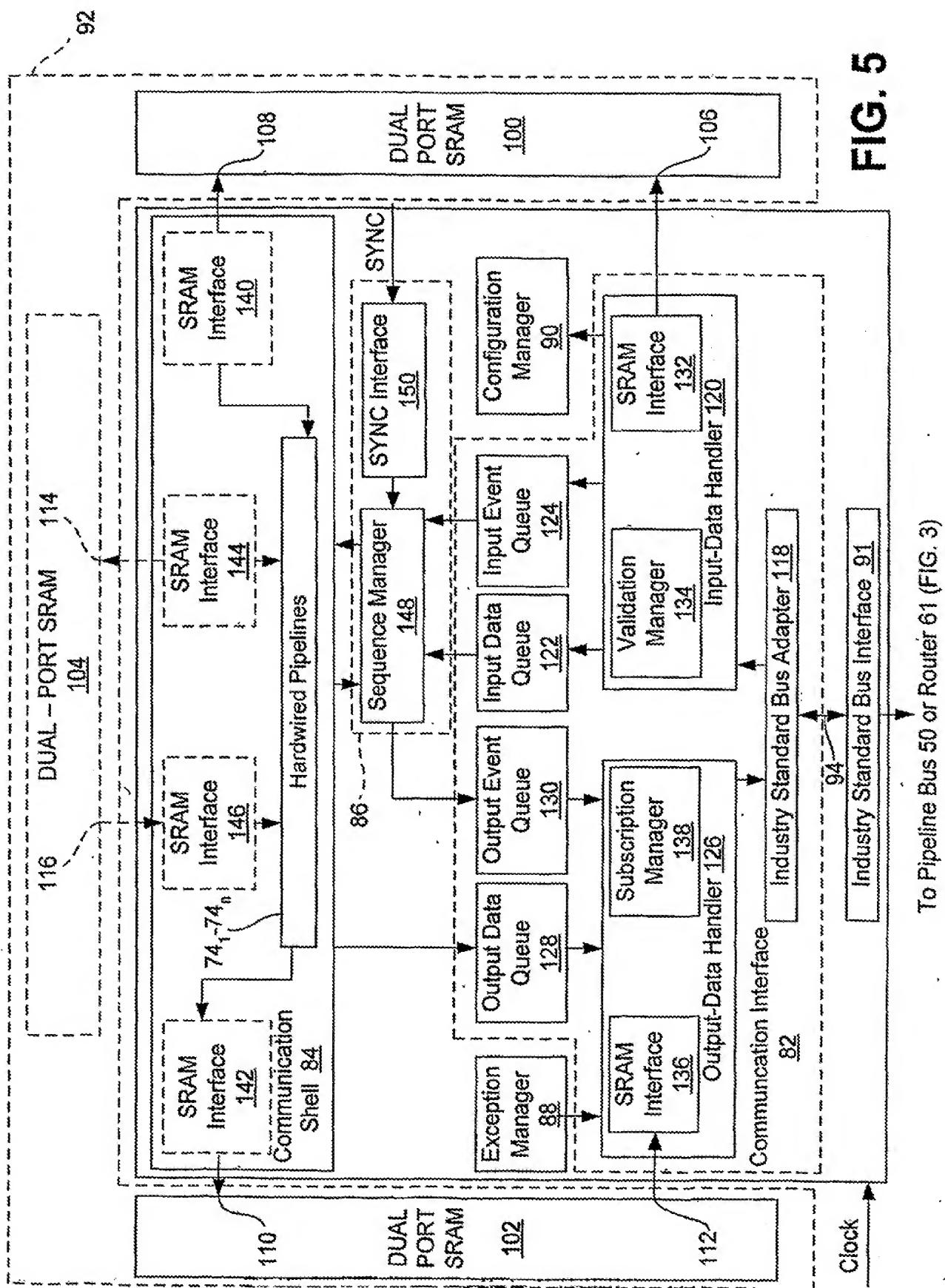


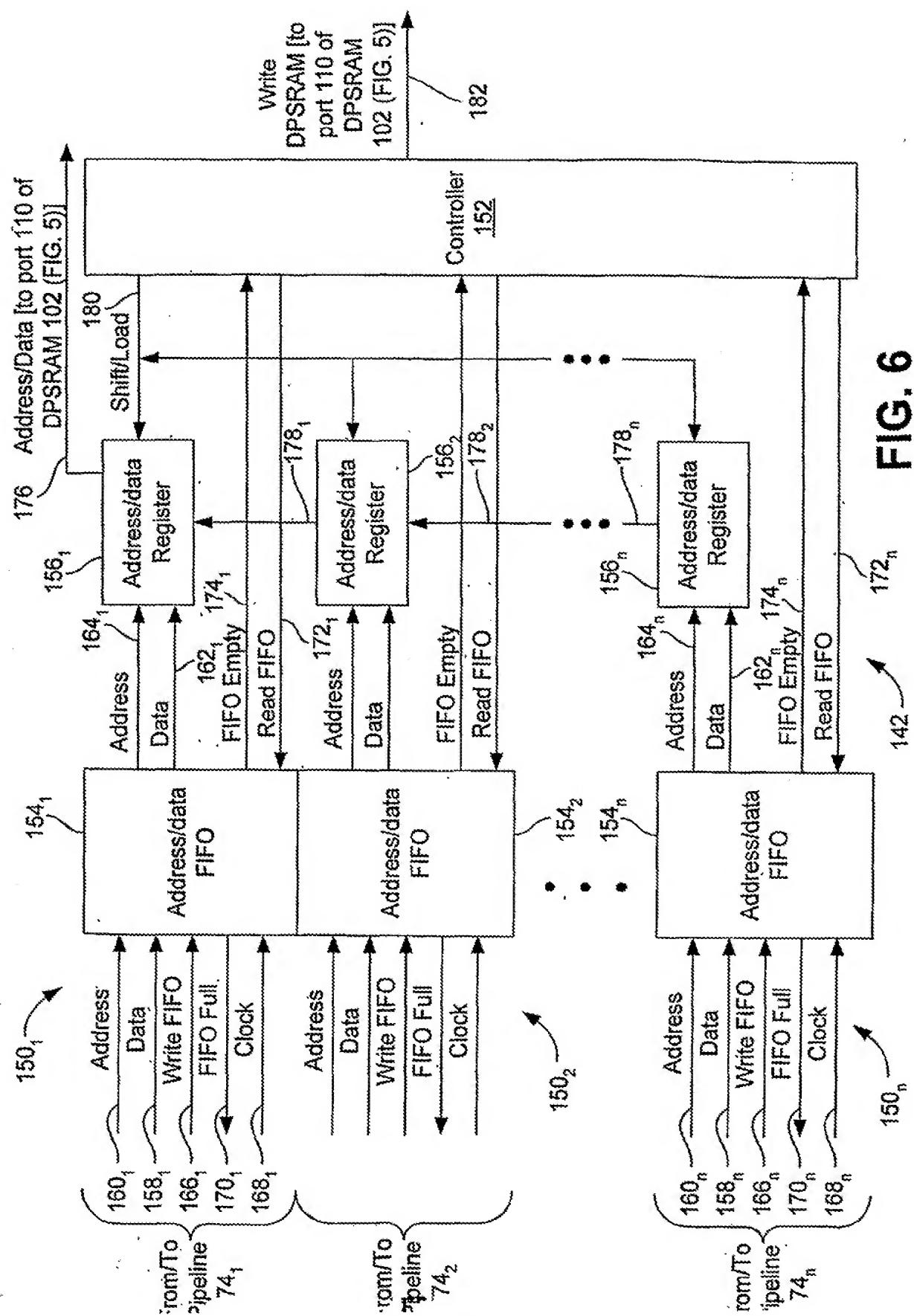
FIG. 2

**FIG. 3**

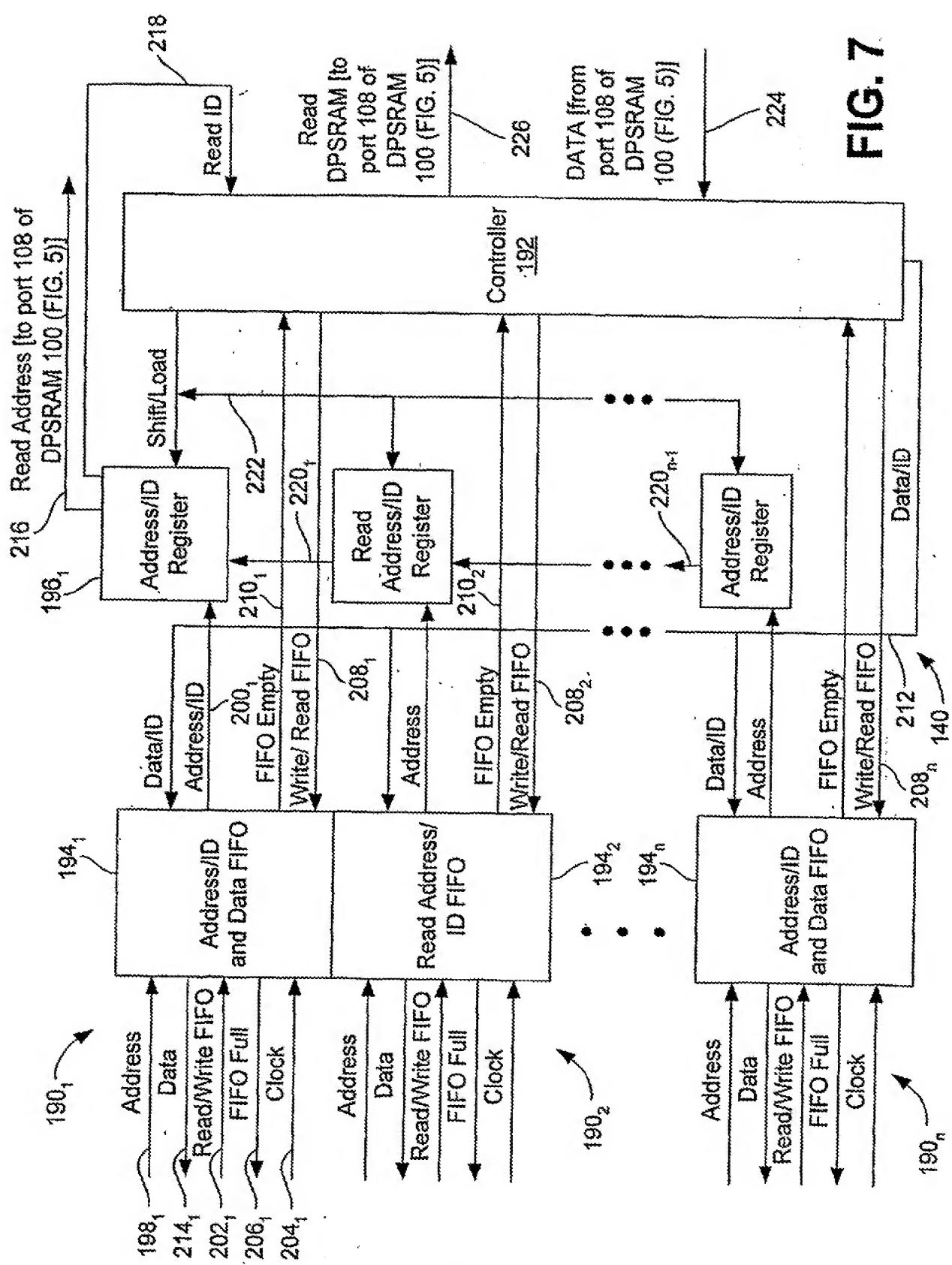
**FIG. 4**

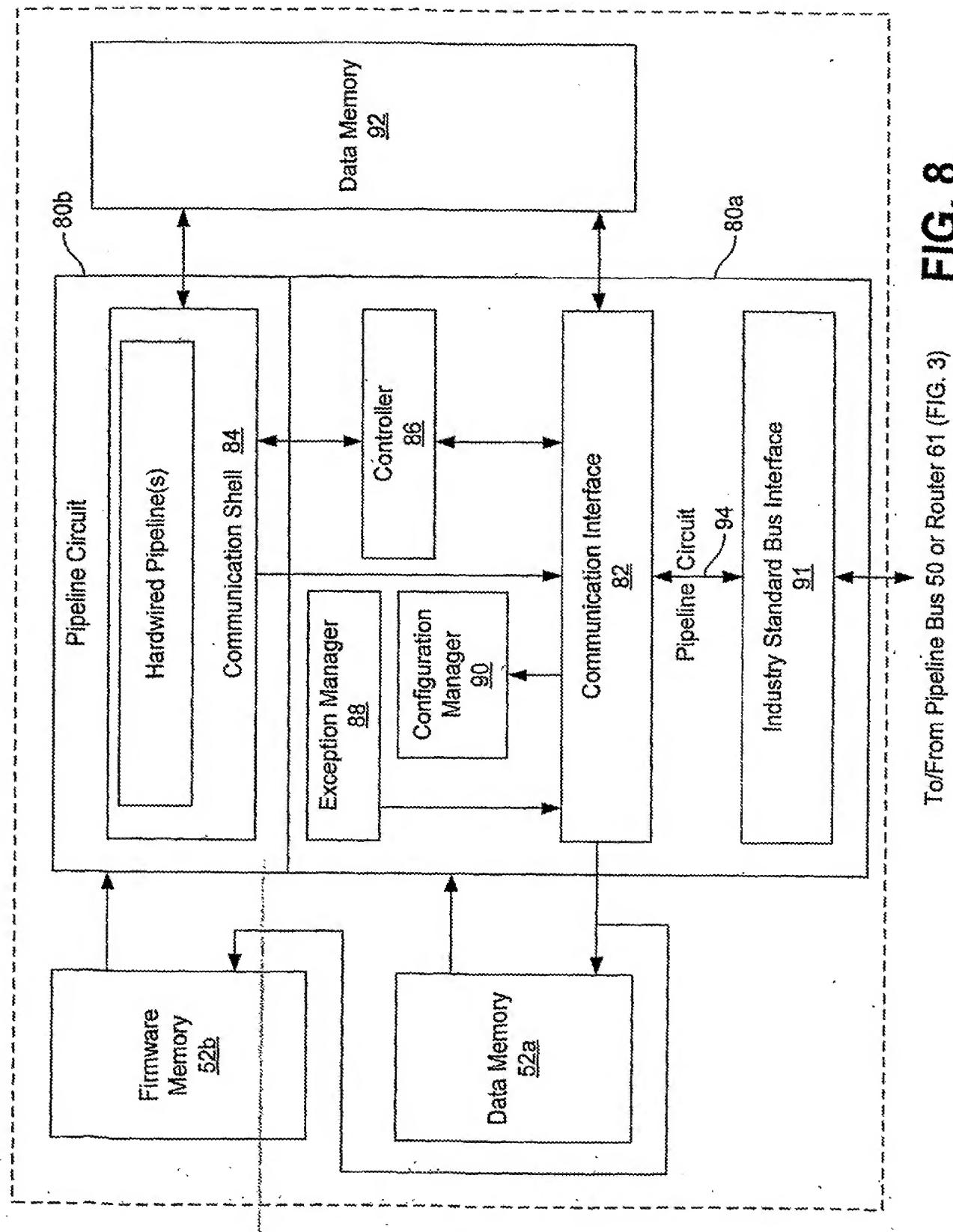
**FIG. 5**

To Pipeline Bus 50 or Router 61 (FIG. 3)

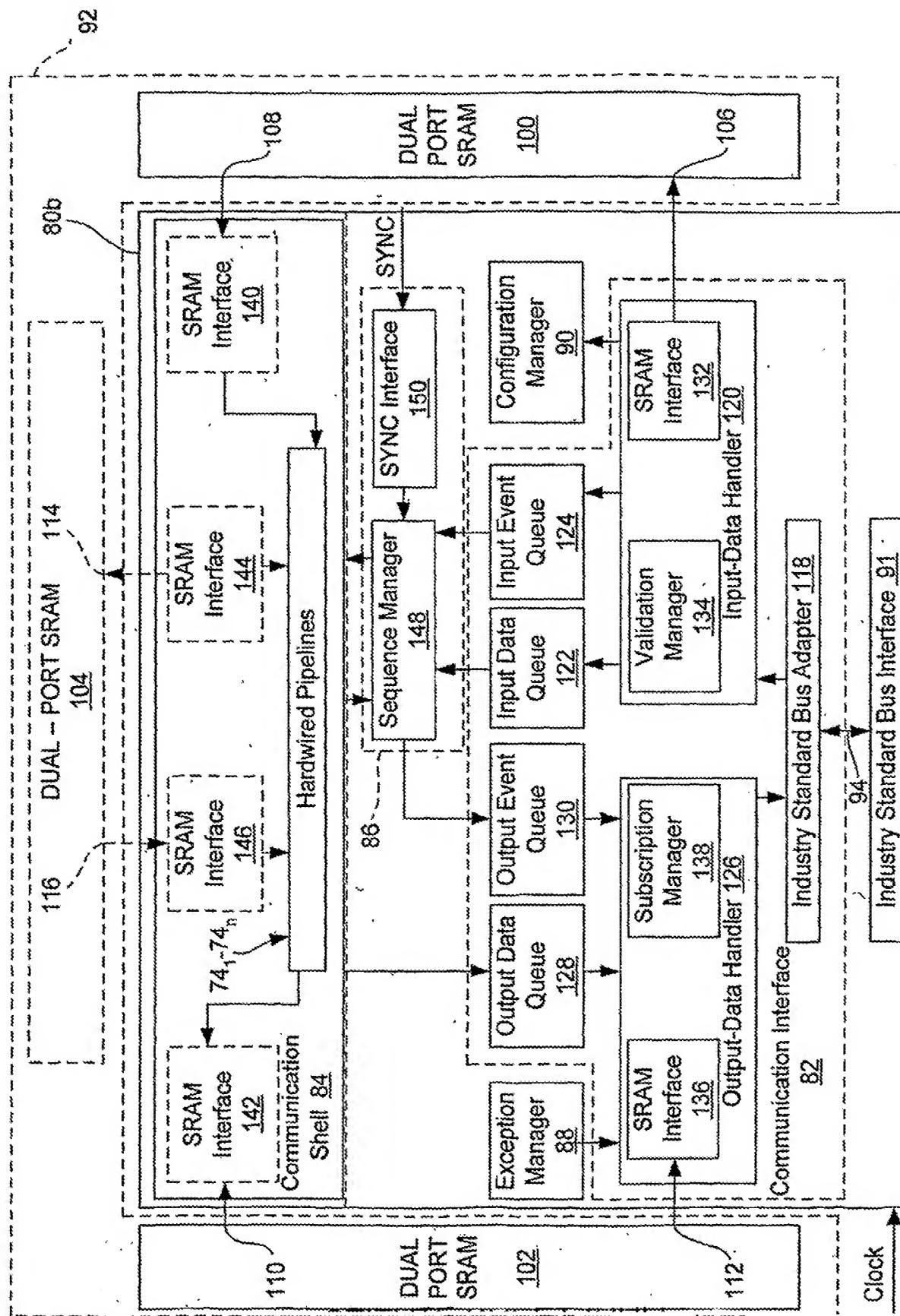


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**FIG. 7**

**FIG. 8**

To/From Pipeline Bus 50 or Router 61 (FIG. 3)

**FIG. 9**

To Pipeline Bus 50 or Router 61 (FIG. 3)